Design of a Multi-Fingered, Passive Adaptive Grasp Prosthetic Hand: Better Function and Cosmesis

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Master of Applied Science, 1998, Nikolai Dechev,
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Abstract

The design of a child sized prosthetic hand capable of passive adaptive grasp is the primary goal of this research. Adaptive grasp is the ability of the fingers to conform to the shape of an object held within the hand. When the hand closes around an object, the four fingers and thumb flex inwards and independently conform to the shape of the object. The grasp of objects such as a cube, a ball, or a pyramid will result in a different final grasp configuration for the fingers and thumb. This adaptability is passively achieved by the mechanisms within the hand. The resulting design is simple and effective, not requiring sensors or electronic processing. The purpose of this hand is to provide a more secure grasp of objects, as well as to improve the dynamic and static cosmesis of the hand, so that it looks as natural as possible.

A prototype hand has been built with four fingers and a thumb. All the digits can curl as they flex and straighten out as they extend. In addition, the thumb can be passively rotated to adduct or abduct. A cylinder spring mechanism has been created to achieve the passive adaptive grasp. Other experimental hands exist with similar functions, however, the digit design, the thumb rotation design and the adaptive grasp design are unique to this project. The major contribution of this work was the creation of these three unique design features and combining them in such a way that the prototype hand is smaller and lighter than any other experimental hand in its class.

Bench testing of the hand reveals that it is currently too slow and uses too much energy compared to conventional prosthetic hands. Also, the hand exerts less pinch force than conventional hands. Recommendations to solve these problems have been made. It can be concluded that the hand increases both dynamic and static cosmesis. Further testing will be required to determine if the hand increases grasp stability. The hand needs to be tested with subjects with lower arm limb deficiencies, so that other potential problems or benefits can be uncovered.

Acknowledgements

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Chapter 1
Introduction

1.1 Problem Statement

There is a wide variety of commercially available prosthetic devices for people with lower arm limb deficiencies. These devices include passive prostheses, body powered prostheses and electric powered prostheses. Each category of devices has benefits and weaknesses. Electric powered prostheses attempt to combine functionality, cosmesis and an electric power source to create a useful and natural looking artificial hand. However, there are still improvements needed to electrically powered prostheses. Recommendations were made from the staff in the Myoelectrics Service at Bloorview MacMillan Centre. In addition, a recent survey to quantify and rate the issues with current prosthetic devices, was used(1). These sources identified the following unmet needs; flexible fingers, an adaptive grasp, a swivelling thumb and a flatter more natural looking palm. Some of these suggested improvements were aimed at improving cosmesis, some were for improved functionality and some were for both.

1.2 Goals of Thesis

The design of a child sized prosthetic hand capable of passive adaptive grasp is the primary goal of this research. Adaptive grasp is the ability of the fingers and thumb to conform to the shape of an object held within the hand. When the hand closes around an object, the four fingers and thumb should flex inwards and independently conform to the shape of the object being grasped.

The design should be simple, effective and reliable. A prototype hand is to be built and evaluated. It will be compared to conventional prostheses and an attempt will be made to determine if the hand can provide a more secure grasp of objects, as well as to improve the dynamic and static cosmesis of the hand.

1.3 Thesis Overview

Chapter 2 - Conventional and Experimental Hands, and the Need for a New Hand

A brief overview of some conventional prostheses, as well as a more in-depth review of some experimental designs was done. The needs as identified were then reviewed and some requirements were formed for the prototype hand. Also, the design process used for this thesis is explained.

Chapter 3 - Preliminary Designs

A number of designs were considered for use with the prototype hand, but were not implemented for various reasons. Some of the designs did not function properly, while other designs were not appropriate for this project. They were listed and reviewed as a reference for future designs.

Chapter 4 - The Prototype Hand Design

The design theory behind the major sub-systems of the prototype hand was presented. The finger design, the operation of the adaptive grasp system and the design of the thumb were explained in detail.

Chapter 5 - Mechanical Review of the Prototype Hand

After the prototype hand was built, the mechanical aspects of the hand were reviewed. Problem areas were identified and suggestions made for correction of the current hand.

Chapter 6 - Bench Testing Results

Electrical tests were performed which helped to evaluate the prototype hand and to benchmark it against conventional prostheses. Pinch force testing was done as well as pull-out tests, in an attempt to evaluate grasp strength and stability.

Chapter 7 - Recommendations

Recommendations were made for the improvement to the theoretical design of the prototype hand. These recommendations would involve more design work and were aimed at solving the shortcomings of the prototype hand. The two major recommendations given, were implementation of an automatic two speed transmission and the creation of a glove designed specifically for this hand.

Chapter 8 - Conclusion

A summary of the needs stated along with the results achieved was given. Also, a summary of the major recommendations was made to address any needs that were not fulfilled.

Appendices

Some computer simulation samples and diagrams of the dimensioned components of the prototype hand were given. Also included were motor selection calculations and specifications. Electric current and energy consumption graphs along with more details of the bench test results were given. Finally, specifications of conventional prostheses, as well as some pictures of the prototype hand during testing were provided.

Chapter 2

Conventional and Experimental Hands, and the Needs for a New Hand

2.1 Conventional Prosthetic Hands

A review of three conventional, electric powered prosthetic hands is presented. These three hands are typical of the type of prosthesis that is currently fitted onto amputees by the Myoelectric Service at Bloorview MacMillan Centre. The purpose is to outline the function and design features of these hands.

2.1.1 The VASI 7-11 Hand

This prosthesis is one in a series of child sized prosthetic hands. It is shown below in Figure 2.1. As the name implies, it has been designed for the age group of 7 to 11 years. The main components of the prosthesis are the palm and two opposing links.

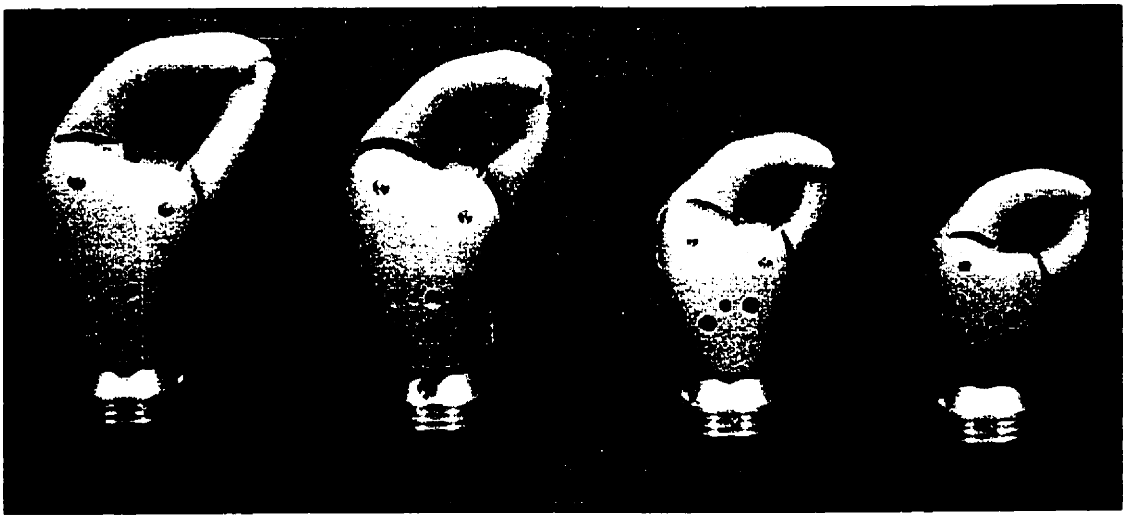


Figure 2.1 VASI hands, from left to right, 7-11, 5-9, 2-6, and 0-3 (3)

One of the opposing links is the thumb and the other link is the index and middle finger pair. These two fingers do not move with respect to each other, but are one solid piece. The finger pair link and the thumb link are coupled by gears, giving the device one degree of freedom. The specifications and dimensions of the hand are listed in Appendix F4.

The weight of the hand without a wrist unit and without a glove is 198 grams. The fingers are sized appropriately for the age group, however, there have been complaints from users(2) that the hand appears too 'boxy' or 'fat' at the palm area. This seems to be an unavoidable aspect of the design, since the motor and other components are all placed within the palm.

The hand can exert a pinch force of up to 9 lbf (40 N). The staff in the Myoelectrics Service feel that, for a majority of tasks, this is sufficient pinch force. However, they also mentioned that some tasks, such as using a knife and fork, require more pinch force.

The control system of the hand has been designed and built at Bloorview MacMillan Centre. It consists of a proportional controller using two EMG (Electro myographic) sensors, to vary the closing and opening speed of the prosthesis.

2.1.2 The Otto Bock Electrohand 2000

The Otto Bock Electrohand 2000 prosthesis is aimed at the same age group as the VASI 7-11 hand. It is shown in Figure 2.2.

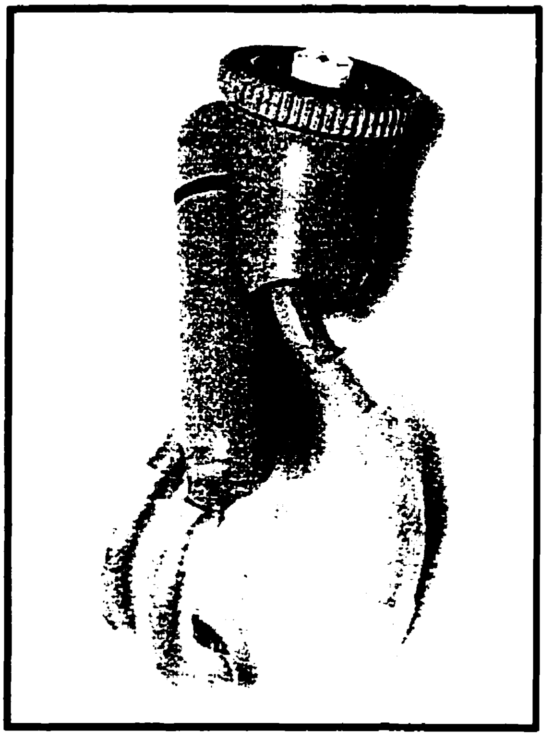


Figure 2.2 Otto Bock Electrohand 2000(4)

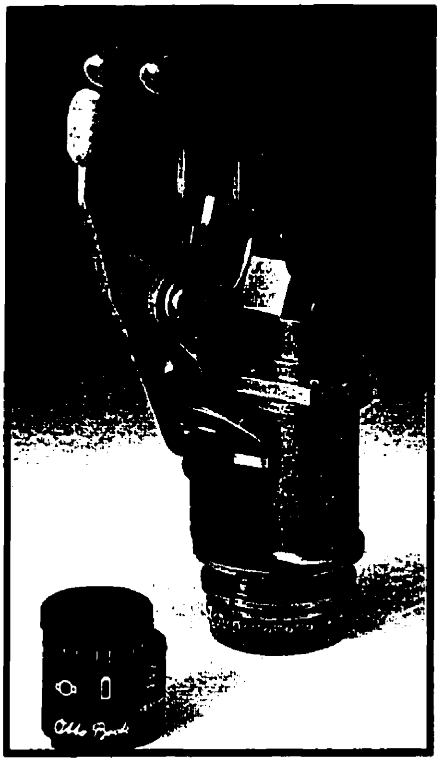


Figure 2.3 Otto Bock 7 1/4 Hand(4)

The main components of this hand are the palm, a link in the shape of two fingers and a link in the shape of a thumb. Operation is similar to the VASI hand, that is, there is one degree of freedom for the open and close task. The hand is slimmer than the VASI 7-11 hand and as such, is considered to be more cosmetic(2). The specifications for this hand are listed in Appendix F3. The weight of the hand without the wrist and glove is 130 grams(4).

This hand uses two motors, one for a high speed close and the other for a high torque (resulting in high pinch force) close. This two stage system optimises the hand for high speed and high pinch, while minimising total motor and gearbox volume. The hand is capable of a pinch of 12 lbf (55 N). It is controlled with proportional control using two EMG electrodes.

2.1.3 The Otto Bock 7 1/4 System Electric Hand

This hand is sized for women or adolescents and is therefore larger than the two prostheses previously mentioned. It employs a similar system of one link acting as two fingers, one link acting as a thumb, and the palm which connects them. The mechanism has one degree of freedom, for open and close. The hand is shown in Figure 2.3.

The hand weighs 480 grams with the inner glove, but without the outer glove or wrist. It is capable of a pinch force of 27 lbf (120 N), which is possible with the use of a two speed automatic transmission, used by this prosthesis. It allows for a relatively fast close, followed by a high pinch force as the transmission gears down. This hand is controlled by a proportional controller using two EMG electrodes.

2.2 Experimental Hands

Four different experimental hands are reviewed. They are, the Montreal Hand, the Southampton Hand, the Belgrade/USC Hand and the Utah/MIT Dexterous Hand. They have been specifically chosen because they are very similar to each other in appearance and function. Also, these experimental hands have design features that are applicable to the proposed prototype hand for this project. Each experimental hand has its strengths and weaknesses. They are presented in order of most applicable as a prosthesis, to least applicable. All of the hands reviewed have flexible digits, adaptive grasp and the ability for thumb adduction and abduction.

The major features of each hand are first reviewed. Next, the experimental hands are evaluated in terms of applicability for prosthetic use. Several important criteria are considered. These are, the purpose of the hand designed, its weight and size, its grasp strength and energy consumption, its control scheme and lastly its cosmetic appearance.

It was sometimes difficult to find design details regarding the size, weight, grip strength or energy consumption of a particular experimental hand. However, these details are important benchmarks against which the proposed prototype hand to be designed, must be compared. They help to ensure that the prototype hand is useful, compared to other experimental hands. Therefore effort has been made to extract as much information from the articles as possible.

One of the criterion for the comparison of the various experimental hands is cosmesis. However, cosmesis is generally an opinion that varies from person to person. After discussions with the staff in the Myoelectrics Service, it was concluded that a prosthetic hand which was considered to be cosmetically pleasing should possess dimensions as close as possible to a typical human hand. This includes finger lengths and widths, palm thickness and general shape. Most importantly, however, it should look natural when it is statically holding an object, or during the dynamic grasping of an object. Another important aspect of hand cosmesis is the use of a glove. Glove colour, texture, and even stretch should look natural. Unfortunately, there are no commercially available gloves made to withstand the strain of flexing fingers, independently closing fingers, or the swivelling thumbs of the experimental hands. The hands reviewed either used a modified conventional prosthetic glove, or no glove at all.

Many of components of the hands described throughout this chapter and the rest of the thesis, are named after the anatomy of the natural hand. A brief review of the diagram in Appendix B, which labels the bones of the hand, may be useful to better understand this work.

2.2.1 The Montreal Hand

The Montreal Hand was designed for the purpose of being an adult prosthesis. It was developed between 1986 and 1992, as a joint project between the Ecole Polytechnique de Montréal and the Research Centre of the Institut de Réadaptation de Montréal. The Montreal Hand uses an adaptive grasp system that is mechanically passive. In a passive system, the mechanics within the palm will align themselves automatically, to adapt the fingers around the object being grasped. There is little detail given of the mechanism that creates the adaptive grasp in the articles reviewed. All that is stated is, "the palm encloses the motor and gear assembly which through an adjustable clutch, drives the two cross shafts. The shafts are mounted with five concentric spring loaded pulleys to which, the cables mobilising the fingers are connected."(5) The clutch that is referred to, is believed to be a 'slip clutch.'(6) Slip clutches operate by transferring torque, up to a specific amount. When that amount is exceeded, the slip clutch starts to slip, thereby limiting the maximum amount of torque transferred. Slip clutches can use up a lot of energy during the slip operation, because the excess torque, above the specified torque of the slip clutch, is lost to friction. Figure 2.4 shows the Montreal Hand holding a pen with a tri-digital pinch.

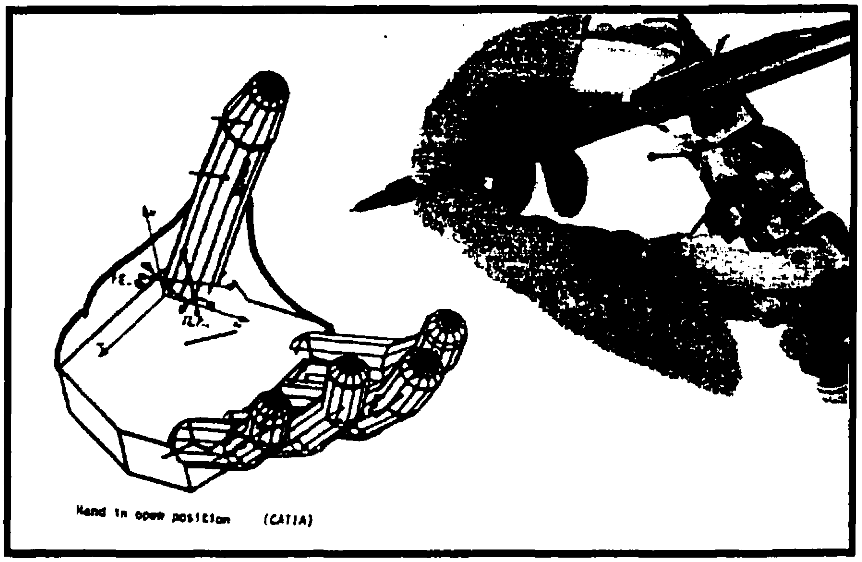


Figure 2.4 The Montreal Hand Grasping a Pen(5)

As part of its adaptive grasp feature, the Montreal Hand had flexing fingers. During a power or spherical grasp, the phalanges of each finger would passively 'wrap' around the object within the hand's grasp. First, the proximal phalanx would encounter the object and its motion would stop while the medial and distal phalanges of that finger, would continue to flex. Next, the medial phalanx would stop when it encountered the object, allowing the distal phalanx to continue flexing, until it too finally encountered the object. The mechanism which allowed for the finger 'wrap' of the Montreal Hand is unknown, other than that it involved cables wound around spring loaded pulleys within the palm.

The Montreal Hand was designed for adult users and was sized accordingly. Nevertheless, one article suggested that future improvements to the hand should include a reduction in the size and width of the hand, and also shortening of the thumb(7). This suggests that the hand was large for its class. The hand weighed 540 grams without the glove. By comparison, the Otto Bock adult hand weighs approximately 480 grams(4) without a glove. Therefore, the Montreal Hand almost fit into the adult size class and fit well within the weight class for its purpose as an adult prosthesis.

No information was found on the energy consumption properties of the Montreal Hand. The Montreal Hand used the same motor and battery that was used in the adult sized Otto Bock hands(6). The maximum tri-digital pinch force of the Montreal Hand was 10.1 lbf (45 N)(7). In comparison, the maximum tri-digital pinch force for the similarly sized Otto Bock adult hand was approximately 20.2 lbf (90 N)(4) to 27 lbf (120 N)(8). Considering that the same motor and presumably the same gearbox were used for both hands, the lower pinch force suggests a lower mechanical efficiency for the Montreal Hand mechanism. The Montreal Hand was designed and analysed with CATIA 3D software(9). Therefore, regardless of the lower efficiency, this was probably the best design possible for the hand, with its flexing fingers, adaptive grasp and swivelling thumb. With the same motor and roughly the same size and weight as the adult Otto Bock hand, the Montreal Hand could produce only 37 percent of the pinch force. Figure 2.5 shows the Montreal hand grasping a cup.

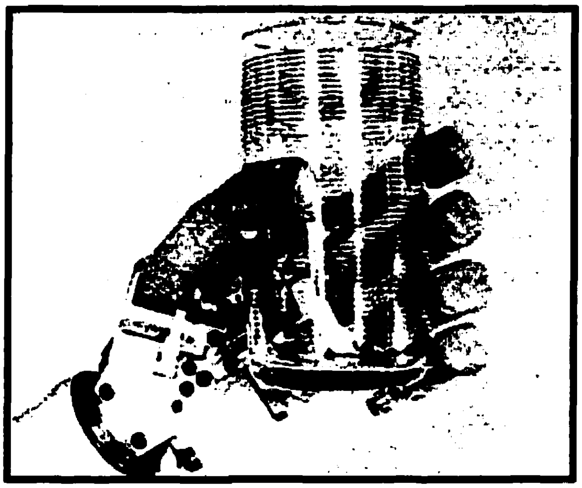


Figure 2.5 The Montreal Hand Grasping a Cup(7)

The Montreal Hand used a relatively simple control scheme to control a single motor. This scheme was basically the same as the Otto Bock dual myoelectric system. That is, one EMG(electro myographic) electrode was used to control opening, and one to control closing. The importance of this design is significant because it allows for the use of standard, proven, off-the-shelf parts in terms of electronics. Also, these technologies are already known to the staff who fit prosthetic hands onto users.

The Montreal Hand was very cosmetic in shape and size, compared to a conventional prosthetic. It was also very dynamically cosmetic(2)(6). Most of this dynamic cosmesis could be attributed to the adaptive grasp feature of the hand. One problem that did exist with the cosmesis of the Montreal Hand was that a conventional glove could not be used with it. The use of a glove would limit the motion of the fingers and would cause a misalignment within the cable system, so that the fingers would not line up(6). For this reason, a glove could not be used on the hand, but only on the finger tips. This took away from the cosmesis because all of the mechanisms were exposed.

The Montreal Hand was designed purely for the purpose of becoming an adaptive grasp prosthesis. It was sized slightly larger than adult size and weighed a correct amount for its adult class. Its pinch force was one third lower than a conventional prosthetic in its class, even though it used the same motor and had roughly the same opening and closing time. Its energy consumption per open/close cycle was unknown. The Montreal Hand's control system was basically the same as the Otto Bock system, which was a dual myoelectric sensor system that operated a single motor in forward or reverse. The hand seemed to satisfy most of the cosmetic requirements, with the exception of the glove.

2.2.2 The Southampton Hand

The Southampton Hand does not describe one prosthesis, but a number of evolving hands that have been made by the University of Southampton since 1969. The complete collection of these designs is collectively referred to as the Southampton Hand. These hands were designed as adult prostheses.

The Southampton Hand reviewed here was the 'third generation, four degree of freedom Southampton Adaptive Manipulation Scheme (SAMS)' hand, which was the most recent of all the designs. The Southampton Hand had two very distinct features. Firstly, the mechanical design of the hand was novel compared to conventional prostheses. It had four fingers with three phalanges each, a thumb capable of adduction/abduction and adaptive grasp. Four motors were used to actuate the hand. One for the index finger, one for the remaining three fingers, one for thumb adduction/abduction and one for thumb flexion/extension. Secondly, the control of the hand was novel compared to conventional prostheses. It used force sensors located on the finger tips, under the medial phalanges and on the palm to detect contact with objects. Depending on the sensors contacted while the hand closed upon an object, a computer decided which type of grasp pattern would be most appropriate and then executed that grasp pattern. In this sense, the adaptive grasp of the Southampton Hand was 'active' and not 'passive' as was the Montreal Hand. A computer actively used sensor information to control the index finger, the three closely coupled fingers and the thumb during adaptability.

The Southampton Hand control scheme used intensity levels (or thresholds) from the flexion signal or from the extension signal to trigger different operation modes (or states) for the hand. When a residual limb is in the relaxed state, it sends no EMG signal to the controller. During this kind of EMG activity level (low) the Southampton Hand automatically flexed closed. If it encountered an object during this close, the computer determined how to best grasp the object, depending on sensor information. After the initial grasp was established, the user had various options available to him/her. Depending on the direction of the EMG signal (flexion or extension), and the intensity of the signal, different instructions could be given to the hand to cause it to carry out different operations. For example the user could flex slightly and issue the HOLD command, or flex strongly and issue the SQUEEZE command. Similarly, he could extend slightly issuing the POSITION command where he was able to reposition the object within the hand, or he could extend strongly issuing the RELEASE command. In this way the control of the hand was much more versatile than the conventional open/close system.

There were no data found regarding the size or weight of the Southampton Hand. The hand was designed for use with an adult, was tested by an adult amputee and therefore was probably adult sized. There were indications of size, in the pictures of the hand being worn by a user(10), where it appeared to be slightly bigger than the natural hand of that user. There were also pictures of the hand that reveal its size, such as those shown in Figure 2.6 and Figure 2.7.

The size of the hand could also be judged by the size of the pen in Figure 2.6, which was assumed to be an ordinary size of about 8 mm in diameter. The motor that controlled the adduction/abduction of the thumb, which can be seen in Figure 2.7, was a Maxon 2017-938 motor(11). The specifications of this motor, in the manufacturer's (Maxon) catalogue(12), reveal that it was 17 mm in diameter and 29 mm long excluding the gearbox. Using these two reference measurements, the palm was estimated to be 100 mm long, 95 mm wide and 30 mm thick.

Since there were no data on the weight of the hand, only estimates could be made about the weight. It used four motors, which were specified by name and type. The four motors together, excluding gearbox weights, were estimated to weigh just over 115 grams. The four gearboxes could weigh an additional 50 grams. The hand appeared to be of mostly metal construction in the figures and it is known that the palm was made from an aluminium block(11). In short, the few observations made seem to point to a hand that was probably heavy.

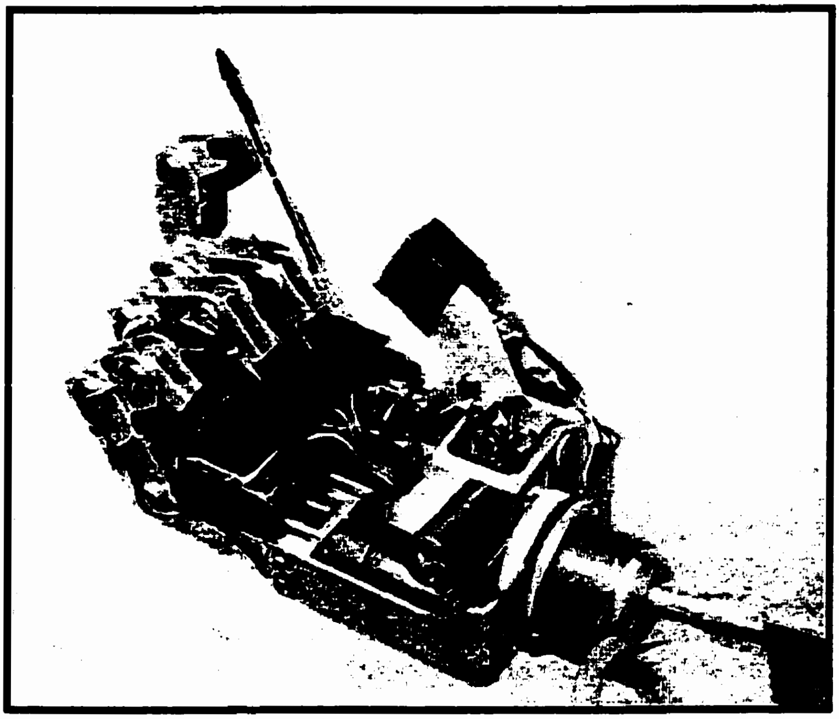


Figure 2.6 The Southampton Hand Grasping a Pen(11)

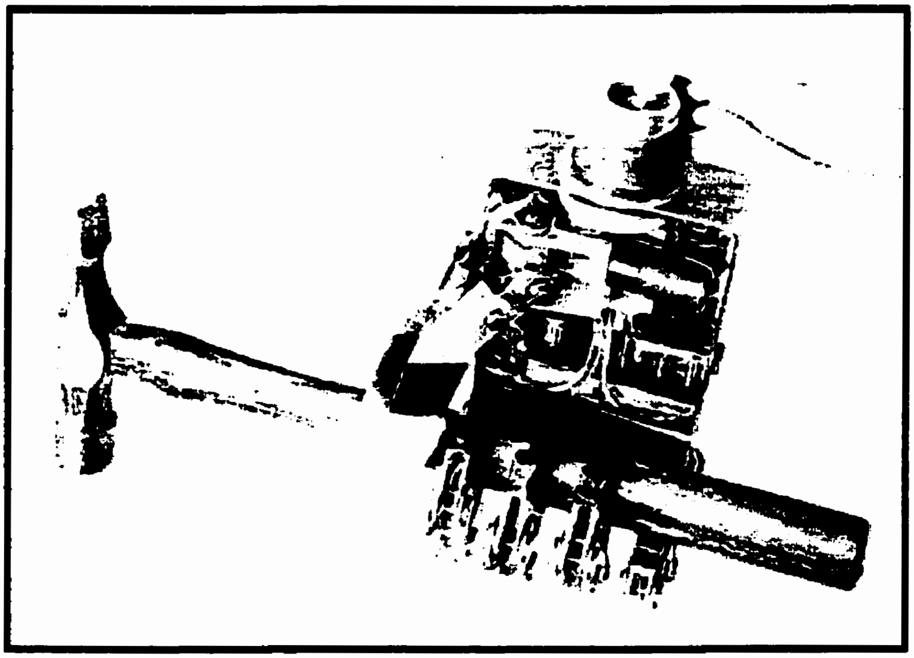


Figure 2.7 The Southampton Hand Grasping a Finishing Hammer(11)

There were no data found regarding gripping forces, or regarding energy consumption of the Southampton Hand. However, there is a lengthy discussion regarding force control of the hand and the sensors that were used to monitor force and slip within the hand. These sensors, the computer and the myoelectric input, controlled the various modes of the hand where objects could be held lightly or tightly, or with minimum force required. Due to the number of motors on the hand and the rated torque of these motors, it is assumed that grip strength and pinch force were high.

Two pictures of the hand being worn by a user(10),(13), both show two cables emerging from the hand and going off the picture. It is unknown what the purpose of these cables was. It is assumed however, that one was for the computer interface and the other was for the power supply to the motors. The manufacturer's specifications revealed that the motor used for the three 'minor fingers' was rated at about 2.7 watts and the motor for the thumb flexion/extension was rated at 1.5 watts. There was no information found for the index finger motor, but it was assumed to be about 0.5 watts, due to its diameter of 12 mm. This would mean the Southampton Hand could use up to 4.7 watts during grasping. The motors specified were 12 volt versions, therefore ten 1.2 volt Nickel Cadmium cells would be required when a battery was used.

The Southampton Hand had single degree of freedom flexing fingers and not independently flexible finger phalanges like the Montreal Hand. Chappell and Kyberd justified their use by stating that they created a more natural looking motion, during closing. "Adopting a defined trajectory gives the curl of the fingers a reasonably natural action ... at the expense of some held objects making contact with a finger in only one or two places."(11) The thumb of the Southampton Hand was not flexible and could not curl like the fingers when it flexed. It was one solid piece that could pivot at two different base joints for flexion/extension, and adduction/abduction.

The Southampton Hand was generally cosmetic in appearance, as it resembled a real hand in shape. According to the articles, it also looked dynamically natural during grasping and statically natural when it was not moving. There was no mention of glove use for the Southampton Hand and all the pictures of the hand were shown with no glove. As a note, it would probably be difficult for the slip and force sensors to function when a glove is worn. The stretching and sliding of the glove, during operation of the hand, could send erroneous signals that could confuse the control system, or skew the threshold values that the system relied on to determine hand states. In this case the Southampton Hand would not be suitable for a conventional glove at all.

To summarise, the Southampton Hand was made as an adult prosthesis. It had single degree of freedom fingers, each of which had a "well defined trajectory which is constrained by the mechanical geometry."(11) It had the adaptive grasp feature, however, unlike the Montreal Hand its adaptive grasp was actively controlled using sensor information and a computer. The weight of the hand was unknown, but the hand seemed to be adult sized, or perhaps slightly larger. The Southampton Hand was not fitted with battery power for the articles reviewed, but appears to have been connected via cable to external power and computer logic. There was no information found regarding any pinch force data, however, due to the fact that four 12 volt motors were used by the hand, it is assumed that a high pinch force could be achieved. No information was found regarding energy consumption of the hand. The control of the Southampton Hand was different from a conventional prosthetic control system. It used the EMG signals from the user to switch the hand through several possible states. When the user was relaxed, the hand would close naturally until it encountered an object. Then user had various options available for further manipulation, depending on the next EMG signal sent. It was a much more versatile system that the conventional one and was said to be quickly learned and easy to adopt(10). The control system could also be used with a single degree of freedom prosthesis(14), such as the Otto Bock hand.

The designers of the Southampton Hand pursued a different design methodology than that of the Montreal Hand. Their design used four motors and sensors to detect slip and force. These sensors, a computer and the SAMS control system were all needed to control the four degrees of freedom of the hand. Due to its increased mechanical and computational complexity, it is placed second to the Montreal Hand as a realisable, practical prosthesis.

2.2.3 The Belgrade/USC Hand

The Belgrade/USC Hand was very similar to the Southampton Hand in terms of design and function. It had four one-degree-of-freedom fingers with three phalanges each. The thumb could not curl as it flexed, but could only flex/extend and adduct/abduct. This hand also used sensors for force control and contact detection. However, there was one fundamental difference between the Belgrade/USC Hand and the hands reviewed thus far. The Belgrade/USC Hand was a robotic hand, intended to be mounted on the end of a robot arm. It had been designed to be anthropometric, but this was done so that it could more easily handle objects used by humans(15). Figure 2.8 shows the Belgrade/USC Hand(Model I) which used a solid thumb.

There were no data found on the size of the Belgrade Hand. However, it can be observed from Figure 2.8 that the hand is holding a ruler with 15 distinct gradations on it, which are probably in units of cms. Therefore, the hand is approximately adult sized.

From the picture, it is estimated that the palm(flat area) was approximately 58 mm long and 73 mm wide. It is also estimated that the fingers were about 90 mm long,17 mm wide and 17 mm thick. There was no rotating wrist on this hand, but rather a bulky area that housed the four motors used by this hand. This area seems very thick for an adult wrist and would not look cosmetic.

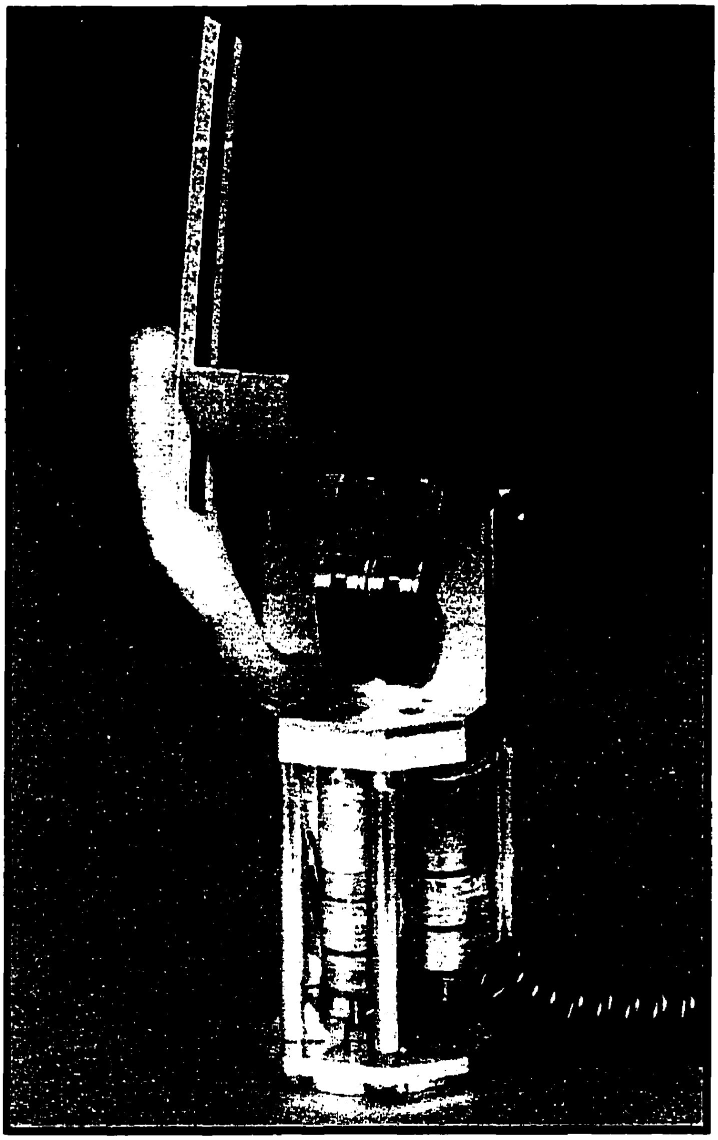


Figure 2.8 The Belgrade/USC Hand (Model I)(15)

The weight of the Belgrade Hand is unknown. However, this hand was intended for use with a PUMA 560 robot, which had a payload capacity of 5 lbs(15). Therefore weight of the Belgrade/USC Hand, combined with any possible payload that the hand would have in its grasp, would need to be less than 5 lbs. Figure 2.9 shows a schematic of the Belgrade/USC Hand(Model II) which was a more recent version. The fingers and palm of Model II hand were the same as the Model I hand, however, the Model II hand had a flexible thumb with two phalanges.

The fingers of this hand were single degree of freedom, having a constant, well defined trajectory during flexion, like the Southampton Hand. The adaptive grasp of the Belgrade/USC Hand was created with the use of three motors. Two of these motors each pulled on two fingers, and the other motor flexed/extended the thumb. Each pair of fingers was connected by a rocker arm, in such a way that as the motor pulled back on the centre point of the rocker arm, it drew the pair back. If one of the fingers encountered an object, the rocker arm would rotate and passively allow the other finger to close inward further. Although the finger pair rocker arm system was passive, the complete four fingered system, including the thumb, used three motors and was actively controlled by a computer to create the complete adaptive grasp.

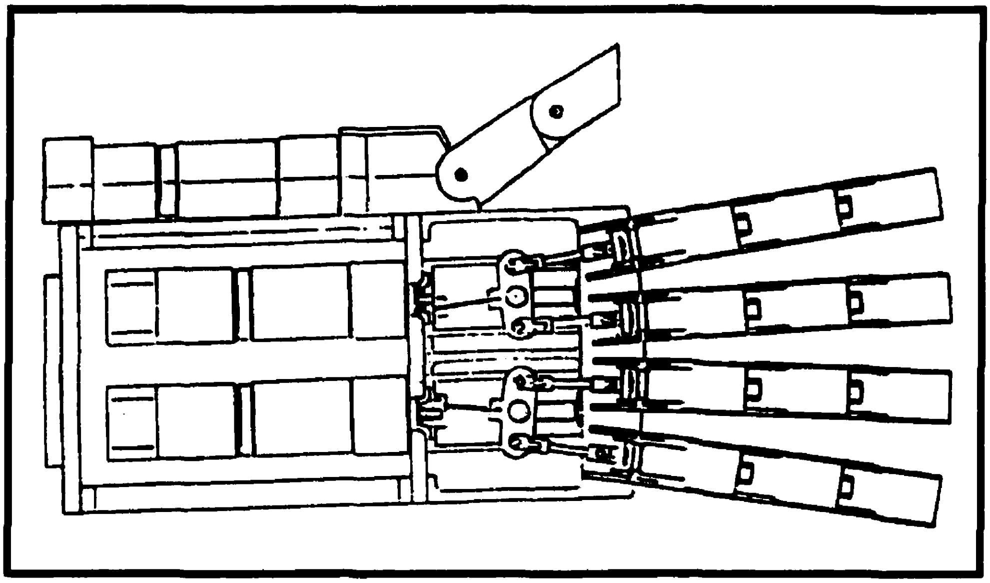


Figure 2.9 Schematic of The Belgrade/USC Hand (Model II)(15)

The adaptive grasp of the Belgrade/USC Hand would have been limited between the finger pairs. These pairs are shown in Figure 2.9, which were the index and middle finger pair, and the pinky and ring finger pair. The adaptive grasp of these pairs was only 'semi-independent' due to the use of the rocker arm. The length between the centre of rotation on the rocker arm to the connection point of the finger link, and the maximum rotation angle of the rocker arm, would define the semi-independence. Whether fully independent motion between the fingers during adaptive grasp is necessary, or whether the semi-independent motion of the Belgrade/USC Hand is sufficient for most grasping tasks is an interesting question that should be studied.

Information was found regarding force control for the Belgrade/USC Hand, however there were no data found regarding any grip force values. The hand used four motors, each of which was 36 volts and had a stall torque of 43 Nmm. Three of the motors had a gear reduction of 30:1, which meant they were capable of 1290 Nmm of torque each, compared to the 56.2 Nmm of torque for the VASI 7-11 hand motor. Therefore, the Belgrade/USC Hand could probably achieve a very high pinch force. Without the force control feedback loop of the hand operating, it would be possible for the hand to damage objects or even itself during grasping(15). Each of the motors was specified as 6 watts. It took three motors to perform a grasp (two for four fingered flexion and one for thumb flexion), therefore this hand could use up to 18 watts during a grasp. In terms of applicability for prosthetic use, 36 volt motors are unacceptable. The motors would need many battery cells, or some form of transformer to increase the voltage of a standard battery pack.

Control of the Belgrade/USC Hand was done with the use of an IBM PC/AT computer, which regulated the voltage levels of the motors via a digital to analogue (D/A) board. A specific bit value would create a specific voltage, which would be applied to the motor. As a note, varying the voltage in this way is not the most effective way to control the speed of motors. The Montreal Hand and the Southampton Hand used an H-bridge circuit configuration and a technology known as pulse width modulation (PWM) to control their motors. This allows for higher torque at lower operating speeds.

The control system for the Belgrade/USC Hand was not designed for EMG input. The only way to operate the hand was via a desktop computer. The manner in which the hand was intended to be controlled however, as noted in the article, was through the use of a knowledge-based system. The computer used a vision system to obtain information about an object's location, orientation and geometry, in order to preshape the hand into an appropriate configuration for grasp. Further, a closed loop control scheme, using finger tip sensors, was used to grasp and hold onto the object. The computers specified for use in this task were either a Sun or TI workstation. It would be difficult to take such computational power and compress it into the typical electronics package required for a mobile prosthetic.

The cosmesis of the Belgrade Hand was lower than that of the other hands. The proportion of the finger length to the palm seemed to be slightly off, compared to a natural hand. In addition, the thumb protruded out halfway down the wrist as shown in Figure 2.9. This hand did not seem to have been intended for use with a glove. Since use of a glove is considered important to cosmesis, this would lower the applicability of this hand as a prosthesis. Lastly, the wrist design was inappropriate for rotation or pivoting, which would force a potential user to use awkward compensatory body motions to allow for use. This would not be cosmetic and would also make the hand difficult to use.

Many of the criticisms made regarding Belgrade/USC Hand were unfair because the hand was made for the purpose of being "an anthropomorphic end effector for robot manipulators"(15). It was not designed for the purposes of being a prosthesis. Regardless, the comparisons were made in order to show its similarities to the other experimental hands and to explain why it would not be suitable as a prosthesis.

2.2.4 The Utah/MIT Dextrous Hand

One of the more notable experimental robotic hands was the Utah/MIT Dextrous Hand. Development of this hand was begun in 1982 and had resulted in the current Utah/MIT Dextrous Hand version IV system. This hand was produced for the purpose of becoming an anthropomorphic end effector for use with experimental investigations of machine manipulation(16). It was a very complex device and considering the complete system as a working whole, was a very large device compared to any prosthetic hand. The hand had three fingers and one thumb, each of which had four degrees of freedom. This included flexion/extension for each of the phalanges in the fingers or thumb and adduction/abduction for a finger or the thumb. This gave the hand a total of 16 degrees of freedom. To control all of these degrees of freedom, the hand used an antagonistic tendon system, where two opposing tendons would control each degree of freedom. Therefore, there were 32 tendons controlling the hand, each of which had its own actuator. The tendons designed for the hand consisted of a multi-layer oriented fibre system. The fibres combined the strength of Kevlar fibres in tension and the abrasive resistance of Dacron fibre which was interwoven with the Kevlar. The goal of these tendons was to have an ultimate strength of 300 N and to last 100 million cycles(17). Various actuators were considered to pull the tendons, including DC servo motors and hydraulic systems, but a pneumatic system was chosen. It consisted of glass and graphite cylinders and a specially designed pneumatic valve. The hand was also equipped with many built-in sensors. These included joint angle and joint torque sensors in each joint, tension sensors for the cables, and depending on the version of the hand, various tactile sensor arrays on the inside of the finger tips or palm.

Figure 2.10 The Utah/MIT Dextrous Hand Version IV(18)

Information on the exact size of the hand was not found, however it was specifically mentioned that the hand was built to " be approximately anthropomorphic in both geometry and size."(17) The reason for doing this, according to the author, was that the natural hand provided proof of a real system that worked well as manipulator, and that it was more easy for an investigator to visualise tasks with a device that resembled his/her own hand. This refers to the fact that this hand was suitable for telemanipulation operations which would use a natural hand master and robotic slave hand system.

Information on the weight of the hand was not found. However, the weight of the hand, the tendons and actuator system must be considered together, as the hand itself would be useless without the rest. It is assumed to be very heavy and for the purposes of this study is not suitable for a prosthesis.

Data regarding grip force values for the hand were not found. The designers of the hand had specified that they wanted the static and dynamic performance levels of the hand to be roughly equivalent to the natural human hand. This included, among other characteristics, speed, strength and range of motion. According to one article, "By contemporary standards, the hand is both fast and strong..."(16) It can therefore be assumed that the Utah/MIT Dextrous hand was at least as strong as a natural adult hand. There were no data found on the energy consumption of the hand. However, considering that 32 actuators were used to drive the hand, the energy consumption would have been high.

This hand was built for the purpose of experimentation with different control strategies. A base system was used to control the actuators and collect data from the sensors. It was a custom built computer based on five 68000 Motorola processors. This system was coupled with a Sun workstation which performed higher level tasks relating to task planning and acquisition of information from a user or input from another system. There were many articles written about different control schemes using the Utah/MIT Dextrous Hand and it is beyond the scope of this work to describe them. Two of these articles describe one of the more interesting applications of the hand, which was telemanipulation(18),(19). Most of the control systems developed for the Utah/MIT Dextrous Hand are not applicable for use in prosthetic control without great modifications.

The Utah/MIT Dextrous Hand shown in Figure 2.10 gives an impression of a precision ,well built mechanical hand. However, according to the definition set forth at the beginning of this chapter, it is not physically cosmetic. Firstly, the hand had only three fingers, each of which was 'thick' in proportion to the rest of the hand. Also, there was no glove for the hand. The original design had called for the use of a glove(17), to protect the hand from the elements and to provide a better gripping surface, but there was no mention of the glove in the subsequent articles. The dynamic cosmesis of the hand however, was probably very impressive. With 16 degrees of freedom and an operating frequency that could approach 20 Hz (compared to a maximum of 6 Hz for the human hand), this hand could probably mimic the human hand better than any of the other designs reviewed, prosthetic or robotic. This assumes that it is provided with a good control system to combine all of the possible motions properly. The adaptive grasp feature of this hand was fully active since it was dependent on the control of the computer. Given so many degrees of freedom and the capability to control individual phalanges independently, this hand could probably perform any grasping function so cosmetically, that if not for its physical appearance, it would be difficult for an observer to distinguish it from a real hand.

The size of the Utah/MIT Dextrous Hand, together with its tendon system and actuators, would make it impossible for it to be used as a prosthesis. It had been included for review to show that even though it was very similar to all hands reviewed in terms of function and appearance, it was not suitable as a prosthesis.

2.2.5 Summary

The four experimental hands that have been reviewed were very similar to each other in appearance and in function. All hands have four fingers(except the Utah/MIT Dextrous Hand) and a thumb that can adduct/abduct and flex/extend. All hands have three phalanges per finger and all hands are capable of adaptive grasp. The Montreal Hand was the only hand with a passive adaptive grasp system. The other hands reviewed used 'active' computer assistance (of varying amounts depending on the hand) to form the adaptive grasp.

The Montreal Hand and the Southampton Hand were specifically made as prosthetic devices. Both have been tested with users and the results compared with conventional prostheses. The Belgrade/USC Hand and the Utah/MIT Dextrous Hand were both made for robotics purposes, and even though they were very similar to the other hands, they were not suitable as prosthetic hands.

2.3 The Need for a New Hand

2.3.1 Limitations Identified with Conventional Prostheses

The staff in the Myoelectric Service at Bloorview MacMillan Centre provided a great deal of input regarding many of the limitations of conventional prosthetic devices, specifically, the VASI and Otto Bock series of prostheses, as these devices were most commonly fitted onto amputees. The information provided by the staff was a mixture of their own opinions and experiences, and also the opinions and experiences of their clients.

One of the more common complaints about the VASI 7-11 prosthesis, was that it did not look 'natural'. It was considered too 'fat' or 'boxy' in the palm area. Also, it did not look natural when a grasp had been achieved, or during the grasp. It looked more like a robot gripper. The cosmesis of the Otto Bock 6 1/2 was considered better, because it had a much slimmer palm. However, it also looked very 'mechanical' during grasping. The importance of the cosmetic appearance was questioned. The staff's response to the cosmesis issue was clear. Younger children were not too concerned with cosmesis, however children in the early teens and teenagers become very self-aware of their bodies and physical appearance. As a result, the cosmetic appearance of a prosthesis aimed at this age group was considered a high priority.

There were also a number of functional complaints about the VASI 7-11 hand. The hand was a single degree of freedom device capable of open and close. As a result, most grasps of objects would result in a two point or three point contact. Also, the fingers were made of rigid plastic and the glove material only provided limited compliance. Because of the limited contact areas and low compliance of the finger tips, high pinch force was required to obtain adequate precision pinches of some objects. The pinch force of the VASI 7-11 hand was not high enough for pinching of objects such as a knife or fork, which will slip out of the hand during use. Also, when larger objects were grasped, a two point contact was often formed. This type of pinch would not properly prevent rotation of objects. If maximum pinch force was not used, heavy objects could rotate out of the grip. The complaints were similar for the Otto Bock series of hands, however, the Otto Bock hands had higher pinch forces, which generally lead to less slipping.

Another disadvantage identified with both designs is a direct result of these prosthetic hands having only one degree of freedom. Because these prostheses open or close in one distinct way, compensatory body motions must be used by the user of the device, when grasping certain objects, to make up for the lack of degrees of freedom of the prosthesis. There are a number of reasons for these compensatory motions, such as limited visibility of the object to be grasped due to the orientation of the prosthesis, a wrist mechanism that limits the ability of the hand to attain certain orientations, or peculiar object sizes or geometries. What the prosthetic hand cannot do, the body must compensate for with upper body, shoulder, and upper arm motion. This leads to awkward body motions that can become tiring after many repetitions, or motions that look very unnatural.

2.3.2 The Needs for a New Hand

There were two main needs identified. Firstly, the new prototype hand should be able to provide improved function for the user. Desired functional improvements would be a more secure grasp with less pinch force, and a hand design that would minimise compensatory body motions. Secondly, the new hand should look more cosmetic. Not only should it look cosmetic in physical appearance, but it should also be more cosmetic during operation. The dynamic cosmesis is the appearance of the hand while it is closing or opening, or the overall appearance of the hand with an object grasped.

2.3.3 The Objectives Selected for the Prototype Hand

There were a number of discussions with the staff in the Myoelectric Service regarding what form a new prosthetic hand should take. A preliminary proposal for the function of such a hand was written and distributed for comment. In addition, there was much discussion about the features of the Montreal hand, some of which were considered beneficial.

It was decided that the prototype hand should generally take the following form. The hand would be designed for the 7-to-11 year age group and should be of an appropriate size and weight in all aspects. It should have four fingers and a thumb which are capable of curling as they flex and straightening out as they extend. Also, the combination of fingers and thumb should be able to close inwards independently, to conform around the shape of a grasped object as closely as possible. In other words, the hand should be capable of adaptive grasp so it can create as many contact points as possible during grasp. It is hoped that this will improve the stability of objects within the grasp. The thumb should be able to adduct and abduct to allow for more grasping options, and therefore hopefully reduce compensatory body motions. The hand should be designed in such a way that a compliant layer of silicone can be attached to the finger tips, fingers and palm for increased surface contact area. Finally, a ball and socket wrist should be made for the hand to further reduce compensatory body motions. The hand should be designed to accommodate such a wrist, which would function in a similar way to the existing VASI OMNI wrist.

The ability of the digits to curl and the thumb to adduct and abduct would presumably make the prototype hand more cosmetic. Also, the trajectory of the curling fingers should look natural during operation. The size of the finger links was to be kept as small as possible to allow them to easily fit into a glove and still leave room for silicone. The palm of the hand is to be kept slim, as this is considered more cosmetic(2).

2.3.4 The Requirements Selected for the Prototype Hand

Based on the objectives for this project, a more specific list of requirements was created before the design process was started. During the design process, whenever a decision regarding the design direction of a particular step was needed, this list was referred to. It served to help guide the design process and to converge on the final design solution.

(1) Children 7 to 11 years of age with a single below-elbow amputation or limb

deficiency, will be using this hand.

(2) The role of the hand is assist in tasks that require both hands. Some suggested tasks that should be considered during design are:

1. Using a knife and fork during meals.
2. Tying shoe laces.
3. Using a computer.

(3) The hand should have adaptive grasp to create as many contact points as possible.

(4) The fingers and thumb should curl as they flex and straighten out as they extend.

(5) The thumb should be capable of abduction and adduction.

(6) Compliant or 'soft' material should be placed on the inside of fingers and palm for increasing the contact area in the hope of reducing 'slip out' of objects.

(7) The hand should be designed for and equipped with a ball and socket wrist.

(8) The motor should be placed within the forearm to reduce palm size.

(9) The hand must be water and dirt proof to the greatest extent possible. In addition, the component materials should be resistant to the elements.

(10) The hand should be lightweight, equal to a natural hand or at least equal to the VASI 7-11 hand's weight.

(11) The hand should be durable. It should be designed to be free of maintenance for 1-year, which is approximately 250,000 cycles.

(12) The electronic control system of the hand should be simple. If possible, a VASI series controller should be used with the hand.

(13) Easily serviceable and easy to repair. The components are to be designed in such a way that there would be minimum service/repair time.

(14) The hand design should be cost effective.

(15) The hand should be able to exert at least as much pinch force as a conventional VASI 7-11 hand.

2.4 The Design Process

The process of designing a complex system like to prototype hand, will vary from designer to designer. There are a number of well known design methodologies and design theories that are available, however, a designer must choose a design process or theory that best matches his own skills and abilities.

Since this is a design thesis, the author would like to describe the design process used in the creation of the prototype hand. This process is highly personal in nature, based on experience and is somewhat difficult to describe. It may or may not reflect the standard design methodologies and other designers may find that this process reinforces or contradicts their own design strategies. Regardless, it is felt that as long as a design meets the original requirements, the process of design is secondary.

First, a set of requirements were selected based on the needs identified. They were then written as shown in Section 2.3.4. The requirements and their associated priorities remain flexible throughout the design. The requirements are not kept in any particular order, and no attempt is made to quantify their priorities. It is enough to keep in mind which are more important and which are less important. This keeps the design process flexible, allowing for new opportunities to be pursued, if they are uncovered during the design process.

Next, the design is split up into its major elements. The process of creating each element of the design is highly iterative. An idea is first created. This idea is then compared to the highest priority requirements, and eventually to all the other requirements. Conflicts with the requirements will result in either a modification of the idea, abandoning the idea, or in some cases, if the idea seems to have high potential to the overall design, modification of the requirements. The process is mostly mental, with the assistance of sketches. The process takes a great deal of time, ideas often occurring randomly throughout the day.

The design of some design elements, such as the trajectory of the curl of the fingers, or designing the fingers to be strong enough, is fairly straight forward. It can be done with computer simulations or engineering analysis. However, the process of creating a finger that will use six links, or creating the way the finger will be actuated, is better described by the previous paragraph.

Once most of the major design elements have been created, they must be combined in a appropriate way to achieve the overall design. It is often difficult to combine the elements, and this process is also highly iterative, requiring many redesigns of the elements so that they fit together. At some point, further iterations in this combining process lead to diminishing improvements. Therefore, one of the final iterations is chosen as the design solution. Unfortunately, there is never one perfect solution, only the best solution of many imperfect combinations.

Chapter 3
Preliminary Designs

3.1 Overview

When designing the prototype hand, a number of different design options were considered. When a decision was made to pursue one design option as opposed to another, the other design was abandoned. The purpose of this chapter is to describe those abandoned designs and to explain why they were not chosen. There are two important reasons for doing this. This work should serve as a reference for the design of multi-fingered, adaptive grasp hands, therefore, it should show the many other possible designs that were considered. Some of the designs were not rejected because they did not work, but rather, because they were not appropriate for the specifications of the prototype hand. In fact, some of these designs were novel, and it is for this reason that they are included. They may satisfy the design needs of some different, future set of specifications. Other designs did not work because they had fundamental flaws. These designs are shown and the flaws explained, so that the same mistakes need not be repeated. If modifications to these flawed designs can be made, they may become usable for a different application.

3.2 Cable Finger Design

The final version of the prototype hand incorporates single degree of freedom fingers. These fingers are detailed in Chapter 4.2. Figure 4.1 shows an accurate diagram of these fingers and the links that comprise them. These single degree of freedom fingers have only one input, or one degree of freedom, that is needed to completely define the shape of the entire finger. However, there is a grasping limitation when using this type of finger. When any of the phalanges of that finger encounter an object, the finger flexion comes to a stop. For example, if the prototype hand grasps an object irregularly in such a way that the proximal phalanx of a finger makes contact first, that finger's motion will stop. The medial and distal phalanges of that finger will be stopped in space, as shown in Figure 3.1. This type of grasp looks unnatural. If the proximal phalanx of a natural hand made contact with the object first, the medial and distal phalanges would continue to flex inward and wrap around the object. This is referred to as 'finger wrap' and is not possible with a single degree of freedom finger. Since this limitation was well known during the start of the prototype design, a finger wrap design using cables was attempted.

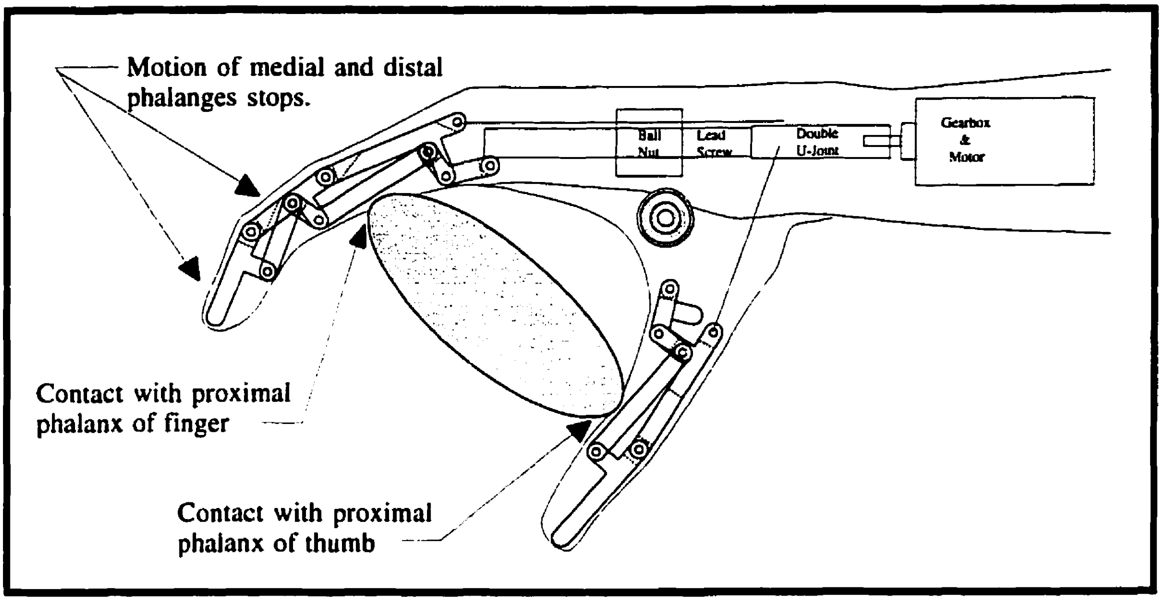


Figure 3.1 Single Degree of Freedom Fingers Grasping Irregularly Held Object

The *Cable Finger* is shown in Figure 3.2. Unlike the single degree of freedom finger which uses six links, the *Cable Finger* uses only three links, one representing each phalanx and makes use of a cable.

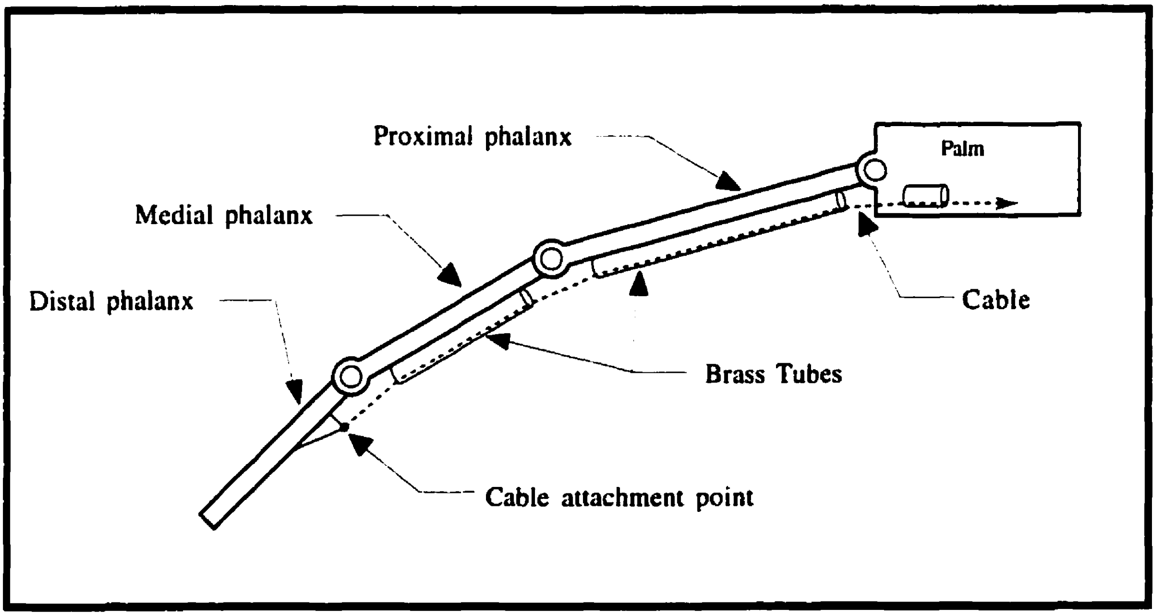
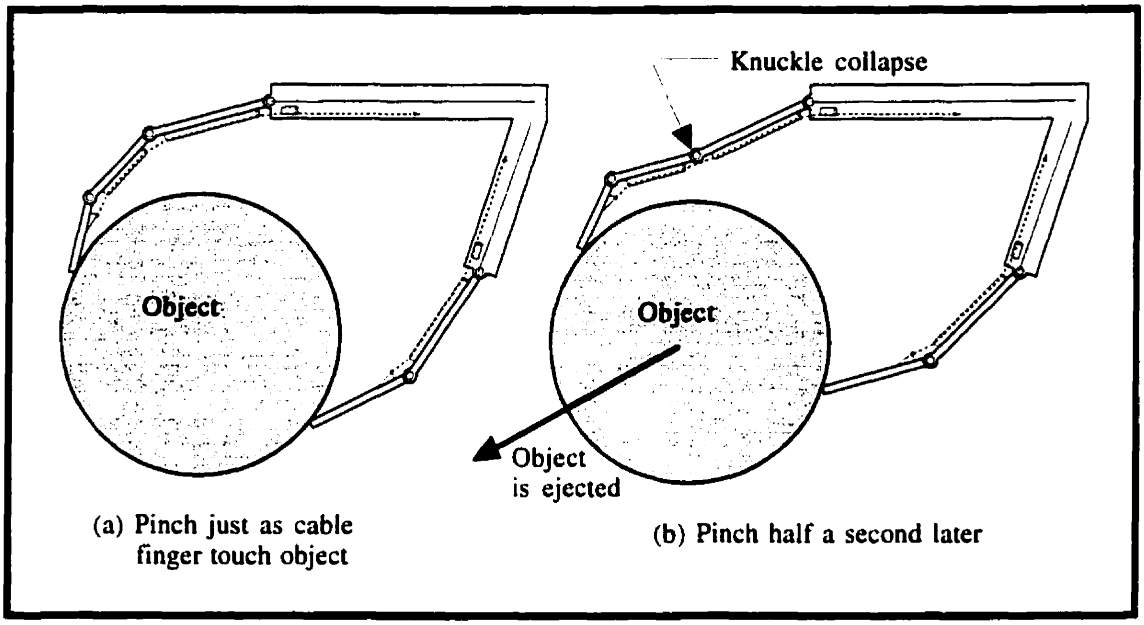


Figure 3.2 Cable Finger Design

The cable is shown as a dotted grey line and runs through brass tubes rigidly fixed onto the proximal phalanx link and the medial phalanx link, and is attached at a point on the distal phalanx link. To operate the finger, the cable is drawn back via an actuator, through the tube rigidly linked to the palm, causing the finger to flex closed. When grasping a large object in a power grip, this design would work reasonably well.

There are some problems with this design however. The first is that this finger design is not appropriate for precision grasping such as a tri-digital or bi-digital pinch. The problem was first noted when an analysis was attempted. There were too many unknowns in the static force equations. Next, Working Model 2D(20) simulations of a bi-digital pinch confirmed the instability. Soon after the bi-digital pinch was formed, the medial interphalangeal joint would buckle inward, as shown in Figure 3.3(b), and cause the pinch to collapse. In the process of this collapse, the object within the grasp would be ejected outwards.



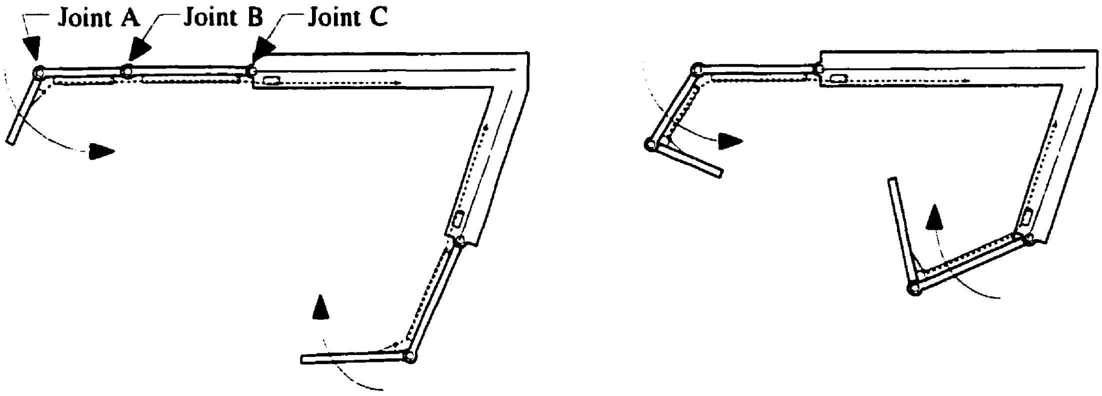
(a) Pinch just as cable finger touch object

(b) Pinch half a second later

Figure 3.3 Unstable Pinch of Object with Cable Fingers

This instability would not occur with fingers using only two phalangeal links, such as the thumb. Because it was decided at the outset of the design, that the fingers used would have three phalanges each, the *Cable Finger* design was not suitable for the prototype hand due to its inherent instability.

Another major problem with the *Cable Finger* design was that the fingers would not close in a curving trajectory suitable for grasping objects. This trajectory was also very non-cosmetic in dynamic appearance. During finger flexion, first the distal phalanx link would flex fully, then the medial phalanx link would flex somewhat, finally followed by the proximal phalanx link. This incorrect trajectory is shown in Figure 3.4. During the close of a natural hand, all of the phalanges flex inward at the same time, with the proximal phalanx flexing through a greater angle during the process. In this way, the natural hand can either pinch an object, or grasp an object and continue to 'wrap' the remaining phalanges around the object. The reason for the incorrect trajectory of the cable finger design can best be explained with the use of Figure 3.4(a).



(a) First, distal phalanx link begins to flex

(b) Next, medial phalanx link begins to close

Figure 3.4 Non-Suitable Closing Trajectory Curve for Cable Fingers

Observe that the cable is attached to the distal phalanx, but only slides through the medial and proximal phalanges via the tubes. When tension is applied to the cable, a torque is developed around Joint A and the distal phalanx rotates, however, the cable does not transmit any force to the medial or proximal phalanges. Only when the distal phalanx fully flexes, can the cable create a torque around Joint B, as shown in Figure 3.4(b).

The *Cable Finger* design needs springs to return the fingers to the open position when the cable tension is relieved.

This design was originally pursued after a presentation of a plastic toy robot hand with flexing fingers, during a Bloorview MacMillan staff meeting. It is interesting to note that the *Cable Finger* design will work under the special condition where the cable is semi-flexible, as was the case for this toy. The cable itself could be a thick nylon or polypropylene tendon, such that when tension is applied to it, the flexing of the tendon defines the finger shape, not the phalanges surrounding the cable. Because the tendon has 'memory' it returns to its original shape after the tension is released, eliminating the need for springs. The only drawback of this design is the great amount of energy that is needed to constantly flex this rigid tendon. Such designs are currently being pursued in California(21).

3.3 Two Degree of Freedom Fingers

The single degree of freedom fingers that have been designed for the prototype hand, as shown in Figure 4.1 of Chapter 4.2 can be converted into two degree of freedom fingers quite easily. The first degree of freedom can control the flexion and extension of the finger, while the second degree of freedom can control the 'curl' or trajectory of the finger. This is achieved by greater control of *Link 6* in the finger as depicted in Figure 3.5.

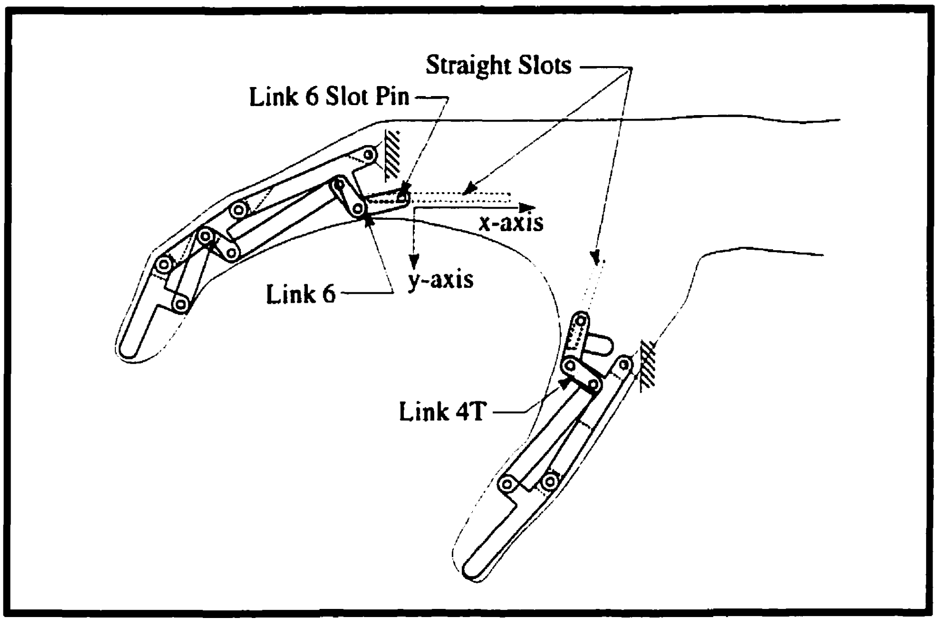


Figure 3.5 Conversion to Two Degree of Freedom Fingers

Link 6 in the prototype hand is connected at three points. One of these points is the *Link 6 Slot Pin* which slides through the *Straight Slot* in the x-axis. If the *Link 6 Slot Pin* is pulled in the positive x-direction, as indicated in Figure 3.5, the finger will flex closed. If it is driven in the negative x-direction, the finger will extend open. In order to add a second degree of freedom to this finger design, a mechanism could be created that could drive the *Link 6 Slot Pin* in the y-direction, in addition to the x-direction. By driving the *Link 6 Slot Pin* in the positive y-direction, the finger would curl inwards more tightly during flexion. Alternatively, by driving the *Link 6 Slot Pin* in the negative y-direction, the finger would curl less tightly (straighten out more) during flexion. This curling inward or straightening out motion would be independent of the flexion or extension of the finger. Together, if controlled properly, these two degrees of freedom could add increased functionality and dynamic cosmesis to a hand design.

One of the problems of the two degree of freedom design, is that a second independent actuator system would be needed to control the y-axis motion. This would increase the mechanism complexity and would also require a more sophisticated control program. One way in which to keep the simplicity of the original design and add the increased functionality of an optimum finger trajectory, would be to create a 'curved slot' as shown in Figure 3.6.

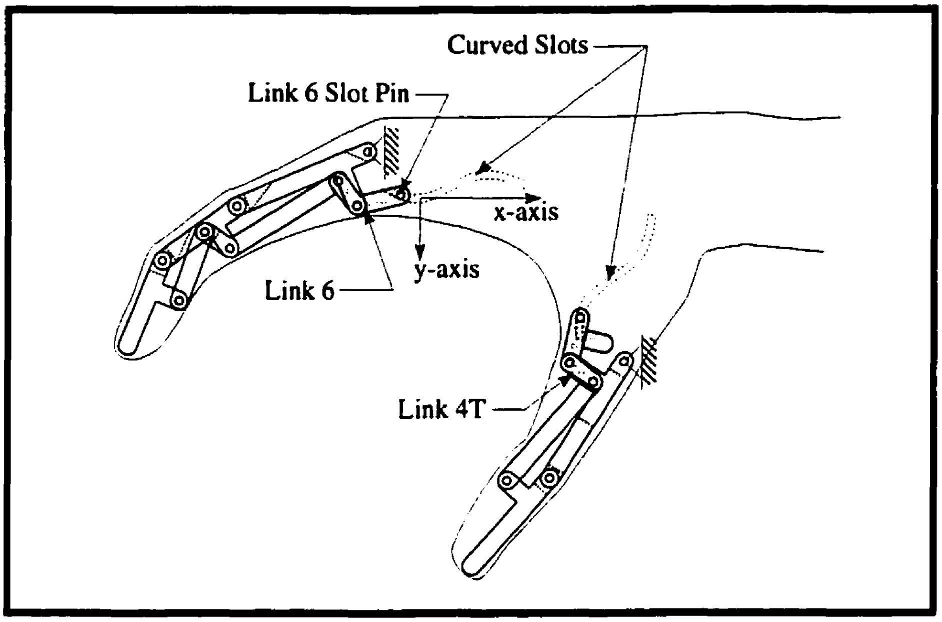


Figure 3.6 Curved Slot Single Degree of Freedom Fingers

With a curved slot design, the finger retains single degree of freedom, but can utilise x-axis and y-axis motion for the *Link 6 Slot Pin*. In this way, an optimum trajectory during flexion and extension can be created for each finger in the hand. A study would have to be performed on the typical finger trajectories of the natural hand, in order to determine which trajectory would be most suitable for each finger. Because the curved slot design is only a single degree of freedom system, once a curved slot is machined into the hand, the finger trajectory would be fixed, as it is in the straight slot design in the prototype hand.

3.4 Spring Adaptive Grasp System

The system initially chosen to create the adaptive grasp for the prototype hand was the Spring Adaptive Grasp System. It was a fairly simple system that utilised tight wound extension springs, and is shown in Figure 3.7. At one end, each extension spring was connected to the *Link 6 Slot Pin* and at the other end, all extension springs were connected to the *Force Plate*. The *Force Plate* was connected to the *Ball Screw*, which drove the *Force Plate* back towards the wrist during finger flexion, and forward during finger extension. Without these springs included, the mechanism in Figure 3.7 would come to a stop when any one of the fingers encountered an object. Since the purpose of adaptive grasp is to allow the remaining fingers to continue flexing inward until they each encounter the object independently, the extension springs in the design allowed for this adaptive motion. As the *Force Plate* was drawn back, its motion was transferred through the extension springs, to *Link 6* of each finger, causing all of the fingers to flex closed together.

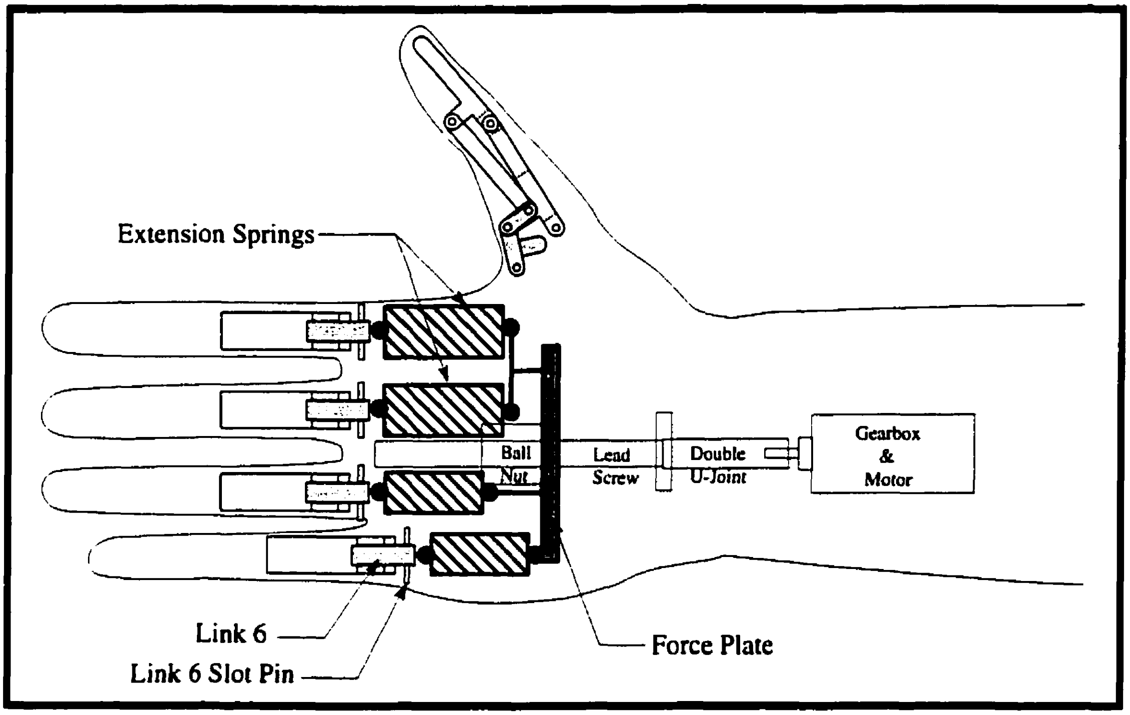


Figure 3.7 Spring Adaptive Grasp System

Because the extension springs have a pretension of 10 N, they can transfer up to 10 N of force without extending. If a finger encountered an object, during pull back by the *Force Plate*, that finger would stop flexing. As the *Force Plate* continued to be drawn back, the force transferred through the extension springs of the 'stopped' fingers would increase until their springs would start to extend. The remaining fingers would keep flexing until they too encountered the object. Eventually, all of the force available from the *Force Plate* would be distributed among the fingers. The force that each finger tip would exert on the object it contacted, would be proportional to the extension of the spring connected to it. The greater the extension of the spring, the more force that would be transferred to a finger.

This system had two fundamental problems. During simulations with Working Model software, it was found that the bi-digital pinch was unstable. The instability occurred because the extension springs could not equalise the force upon formation of a final pinch. Because the springs were in tension independently of each other, there was no feedback within the mechanism to balance the forces. The length (extension) of these springs varies with the amount of force they transfer. Depending on the size of an object that is pinched and the location of that object with respect to the finger tips, the forces required to stabilise the grasp are different. Due to these differing forces, the fingers and thumb would start shifting positions in an attempt to balance the forces. This shifting would usually cause the object being pinched to get ejected in the process. This process is shown in Appendix A.1. One way to solve this problem is to add a 'mechanical' feedback loop to equalise the forces, but unfortunately, this increases the complexity of the mechanism. This system was named the *Equalizer*, and is described in Section 3.5.

Another problem encountered was that the tension in the springs could become as high as 130 N per spring, thereby creating a pinch hazard. If an object was grasped or pinched with maximum force, the adaptive springs would have a high tension. If the object was suddenly removed from the grasp, there would be no resistance for the fingers to close inward. Extension springs in tension with 130 N would accelerate the fingers inward, and anything encountered by the fingers would be pinched. Simulations with Working Model software showed that transient tip pinch forces during this condition could be up to 250 N. The problem is that a child might use his able hand to remove an object suddenly from this pre-prototype hand. As a result, while the object is being removed, the fingers would 'snap' inwards, pinching the natural hand of the child. Such a scenario is certainly not desirable and for this reason, the Spring Adaptive Grasp System was rejected.

3.5 The Equalizer Mechanism

The equalizer mechanism was necessary to stabilise the pinch of the Spring Adaptive Grasp System. The *Equalizer*, as shown in Figure 3.8, works like a mechanical feedback loop that shifts its position in response to unbalanced forces between the fingers and thumb during pinching. The best way to describe the operation of the *Equalizer* is with an example. Consider the case of the pre-prototype hand, without the equalizer mechanism, grasping a 30 mm ball with a tri-digital pinch. Working Model simulations of this example have shown that when the initial contact between the hand and the ball is made, the finger tips will exert 34 N of force on the ball and the thumb will exert a force of 28 N on the ball. Therefore, a force imbalance exists between the fingers and the thumb, in favour of the fingers. This causes the fingers to close inward further, thereby 'pushing' the ball toward the thumb and forcing the thumb to open. During this process, the fingers and thumb will keep shifting until they can find an equilibrium position where their tip forces match. Unfortunately, for most of the smaller objects, such as the 30 mm ball, the objects rotate out of the pinch and are ejected from the hand, before that equilibrium position is ever reached. In other cases it is impossible for the fingers and thumb to reach the equilibrium position needed to match tip pinch forces.

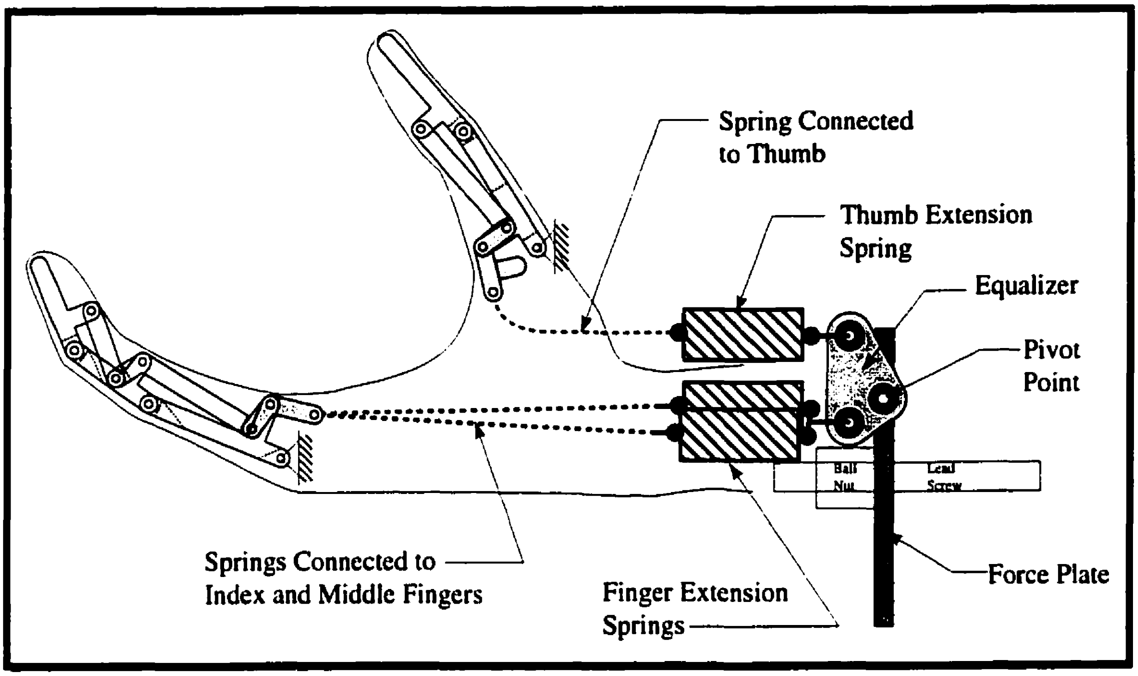


Figure 3.8 Schematic Representation of Equalizer Mechanism

The equalizer mechanism balances these forces and minimises the shifting of the fingers and thumb. In the mechanism of Figure 3.8, the extension springs are connected to the fingers or thumb at one end, and to the *Equalizer* at the other end. When the fingers or thumb flex, their extension spring(s) move back towards the wrist, and when the fingers or thumb extend, their extension spring(s) move forward.

Given the earlier example discussed, the following would occur with the equalizer mechanism installed. Force would be transferred by the *Equalizer* to the fingers and thumb, via the *Pivot Point* pin which is attached to the *Force Plate*. Figure 3.9(a) shows the *Equalizer* in position just after the initial pinch is formed. The *Upper Pin* and *Lower Pin* can only transfer force to the extension springs in the horizontal direction. Their distance, perpendicular to the horizontal, from the *Pivot Point* is 10 mm and 5 mm, respectively. This is a ratio of 2:1 from the *Pivot Point*. Upon formation of the initial pinch, the same imbalance of tip forces from the previous example would occur. Since the finger tips exert more force, they would start pushing the thumb open as before. Therefore, the finger extension springs would move back towards the wrist and the thumb extension spring would move forward, as shown in Figure 3.9(b). Since the finger extension springs are connected to the *Lower Pin* on the *Equalizer* and the thumb extension spring is connected to the *Upper Pin*, this would cause the *Equalizer* to rotate counter-clockwise about the *Pivot Point*, as shown in Figure 3.9(b).

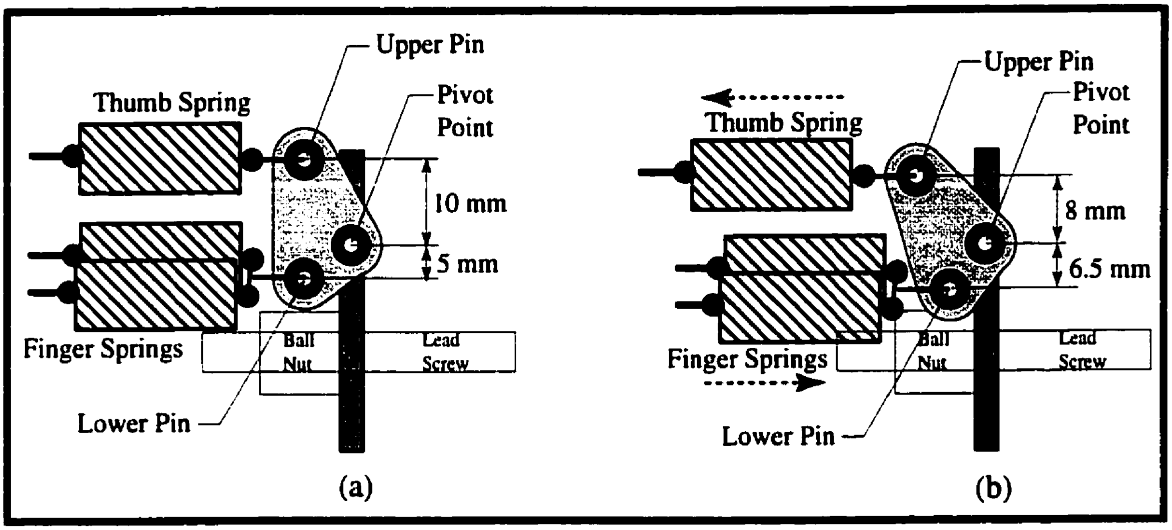


Figure 3.9 Equalizer in Operation

This rotation of the *Equaliser* changes the distance perpendicular to the horizontal from the *Upper Pin* to the *Pivot Point*, and from the *Lower Pin* to the *Pivot Point*. These distances now become 8 mm and 6.5 mm, respectively. This is a ratio of 1.23:1. Simulations showed that initially, in Figure 3.9 (a), the finger springs were loaded with 264 N and the thumb spring with 132 N. In Figure 3.9 (b), after a small rotation of the *Equaliser*, the finger springs are loaded with 218 N and the thumb spring with 178 N, which produces balanced pinch forces of 30.4 N at the finger tips and 30.4 N at the thumb tip. In this way, the rotation of the *Equaliser* can rapidly adjust the force distribution between the finger tips and thumb tip. Therefore, with a small amount of travel of the fingers and thumb, via the rotation of the *Equaliser*, a large change has occurred in the force transferred between fingers and thumb.

The dimensions of the *Equalizer* link determine its effectiveness. The ratio of distances from the *Upper Pin* and *Lower Pin* to the *Pivot Point*, are analogous to the gain in a control system. Also, the sensitivity and reaction time to shifts between the finger and thumb springs, are affected by the overall size (distance from *Upper Pin* to *Lower Pin*) of the *Equalizer*. For this application, the *Equalizer* would ideally be very small, so that only a tiny shift between finger and thumb springs would produce a large rotation of the *Equalizer* and therefore a large and fast shift in force transfer. However, due to the amount of force transferred, the *Equalizer* must be large, to be physically strong enough to withstand the forces being transferred. Also, it must be large enough to accommodate components such as needle bearings, in order to be effective. Unfortunately, the minimum size required by the *Equalizer* by this application was approximately 22 mm long by 15 mm wide. This took up valuable 'real estate' within the hand and would have made the palm an additional 6 mm thicker than the current prototype hand.

The pinch hazard problem of the Spring Adaptive Grasp System, along with the large size of the *Equalizer* needed to balance that system caused the rejection of both designs.

3.6 The Cable Pulley Adaptive Grasp System

There are many limitations when using large springs to create adaptive grasp. Some of these limitations have already been discussed, but another major problem with the extension springs, is that they consume a great deal of energy during the formation of the adaptive grasp. This energy consumption reduces useful operation time of a battery within a prosthesis. An alternative way to create independent adaptive grasp, without the use of large springs is through the use of a cable and pulley system, as shown in Figure 3.10.

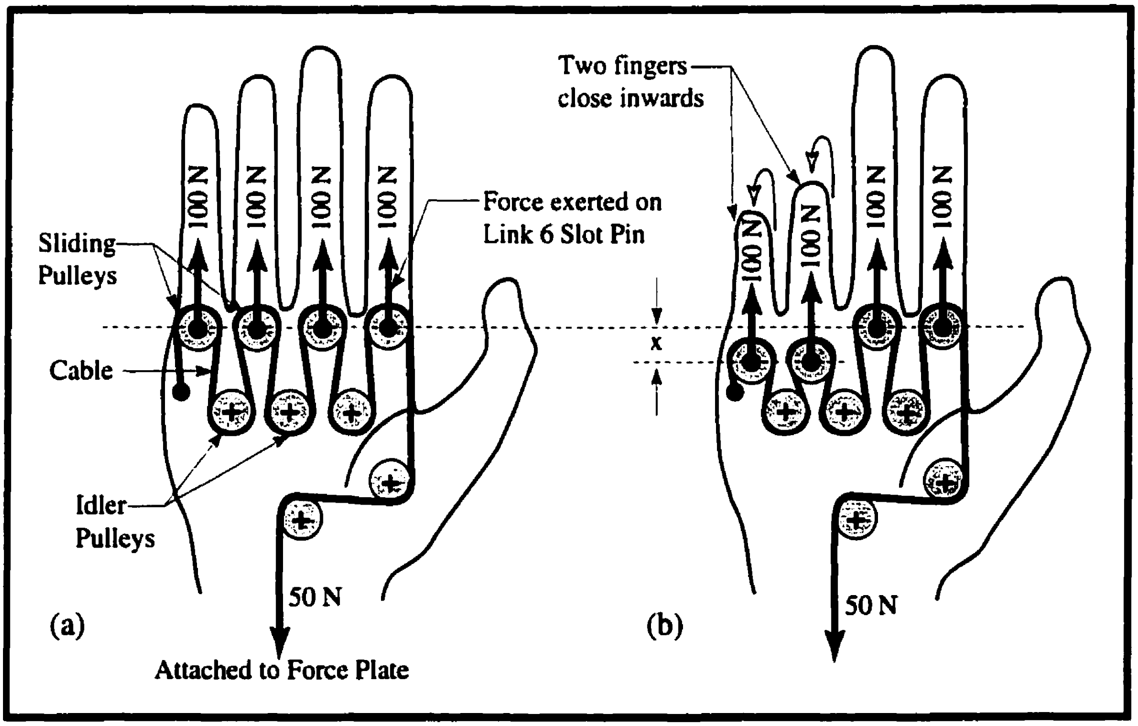
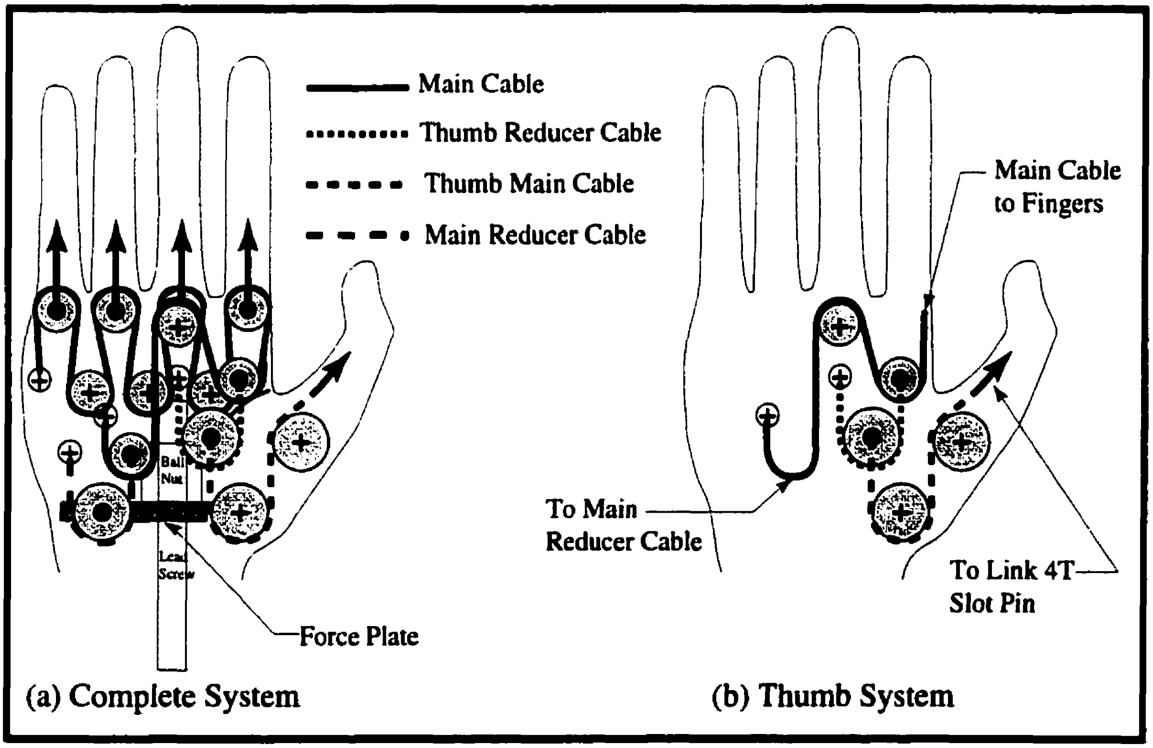


Figure 3.10 Methodology behind Cable Pulley Adaptive Grasp

This system is currently not well suited for performing precision pinches, but is well suited for power grasps. Since this type of hand could be made very small, it could be made for children 5 and under, who have less need for a precision tri-digital pinch(2).

The system consists of a number of stationary *Idler Pulleys*, shown with a '+' through the centre, a number of *Sliding Pulleys* connected to the fingers and a single *Cable*. The *Cable* is wrapped around the pulleys in such a way that when tension is applied to the *Cable* via the *Force Plate*, each *Sliding Pulley* can exert twice the *Cable* tension to its finger, via the *Link 6 Slot Pin*. A spring for each finger would still be needed in this design, to open up the fingers whenever the *Cable* tension is relieved, but such springs can be small, since they only work against mechanism friction. Figure 3.10(b) shows the design in operation. When any of the fingers (for example, the two minor fingers in the diagram) close inward to conform to the shape of the object, their *Link 6 Slot Pin* will move a distance x. This displacement can be denoted x_1, x_2, x_3 and x_4 for the index, middle, ring and pinky fingers respectively. The actual displacement of the *Cable* would be equal to $2*(x_1+x_2+x_3+x_4)$. Therefore a great amount of displacement of the *Cable* is necessary to create the adaptability of the fingers. This can be reduced by 'gearing down' the *Main Cable* as shown in Figure 3.11. Here, an actual working design, with the thumb included as part of the adaptive grasp, is shown.



(a) Complete System

(b) Thumb System

Figure 3.11 Complete Cable Pulley System

With the Cable Pulley design, no matter what the final grasp position of a finger is, all fingers will exert approximately the same force upon the object. The amount of finger flexion does not alter the force exerted. Finger adaptability is passive and completely independent from finger to finger. The act of adapting around the shape of an object consumes very little energy since only small 'return' springs are used by the fingers. Finally, because the tension in the *Main Cable* is relatively low (approx 50 N), tight radius of curvatures can be achieved without cycling fatigue of the *Main Cable.*

This situation is different from the Spring Adaptive Grasp System, where the force exerted on a grasped object varies from finger to finger and the force during flexion also varies. As a note, the 'double swing tree' mechanism of the Southampton Hand and the Belgrade Hand also uses low energy, but its adaptive grasp has an uneven force distribution without active computer control and the adaptive grasp produced is only 'semi-independent'.

There is one major problem with the Cable Pulley design, in that there is instability during a precision pinch. Since the fingers are connected to an independent and even force distribution from the *Main Cable,* there is no way to provide feedback to balance an object held with a pinch. This is exactly the same problem that occurred with the instability of the Spring Adaptive Grasp System. Some sort of feedback system similar to the *Equalizer* would need to be developed, to balance the system for precision pinches. However, the Cable Pulley system would work very well for children aged five years and under, who make little use of precision pinches, and make more use of a power grasp. A small version of an adaptive grasp prosthetic hand, specifically for this age group could hold objects securely and look much more dynamically and statically natural, than current hands.

3.7 Summary

A number of different designs have been presented and explained. These designs were not suitable for use with the prototype hand for one reason or another, but may become the starting points for future designs.

Chapter 4

The Prototype Hand Design

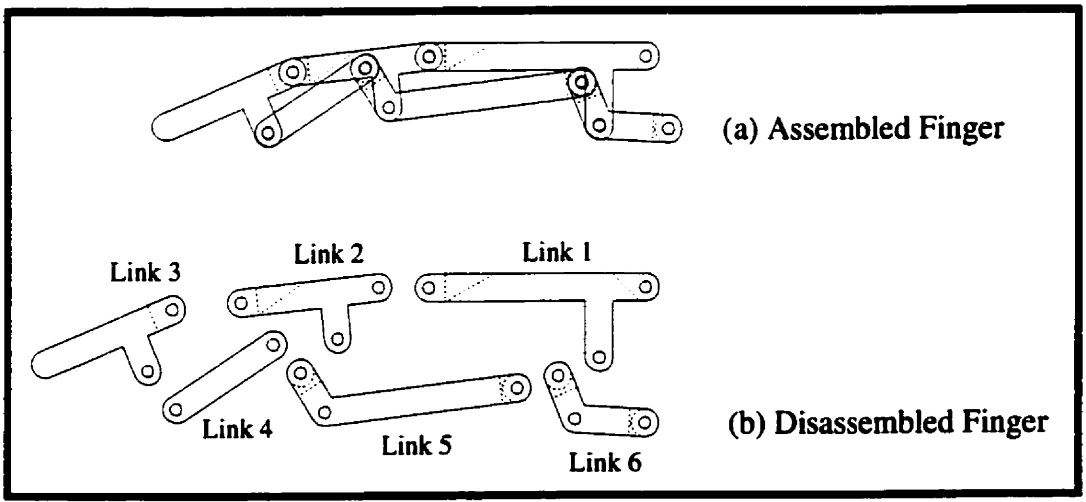
4.1 Overview

The theory surrounding the design of major sub-systems of the prototype hand will be discussed in this chapter. Explanations are given for why the systems were designed the way they were, how these systems work and how they work together.

4.2 Finger Design

When designing the fingers for the prototype hand, four important criteria were used to determine the most effective design. First, the size was established. The overall finger length was to be 65 mm. The internal finger structure was to be a maximum of 9 mm wide and less than 13 mm thick, through the entire range of motion. The design also had to allow for room under the finger tips, for the addition of compliant silicone. Secondly, the fingers were to trace out a path in space that closely resembled the path of natural fingers during a normal grasp. Thirdly, the design was to be as low weight as possible. Finally, the design should maximise the mechanical efficiency of the finger, that is, the ratio of tip force exerted upon an object, vs the input force at *Link 6*.

The fingers of the prototype hand were designed to have the look of a natural finger with three phalanges. Figure 4.1 shows a scaled diagram of the fingers used. *Link 1*, *Link*


(a) Assembled Finger

(b) Disassembled Finger

Figure 4.1 Single Degree of Freedom Finger

2 and *Link 3* represent the proximal, medial and distal phalanges, respectively. *Link 4* and *Link 5* are 'coupler links' and *Link 6* is the 'driver link', that drives the finger through its motion.

The fingers that are used with the prototype hand have a single degree of freedom. All the finger links have a specific orientation with respect to each other, depending only on the x-position of the *Link 6 Slot Pin*.

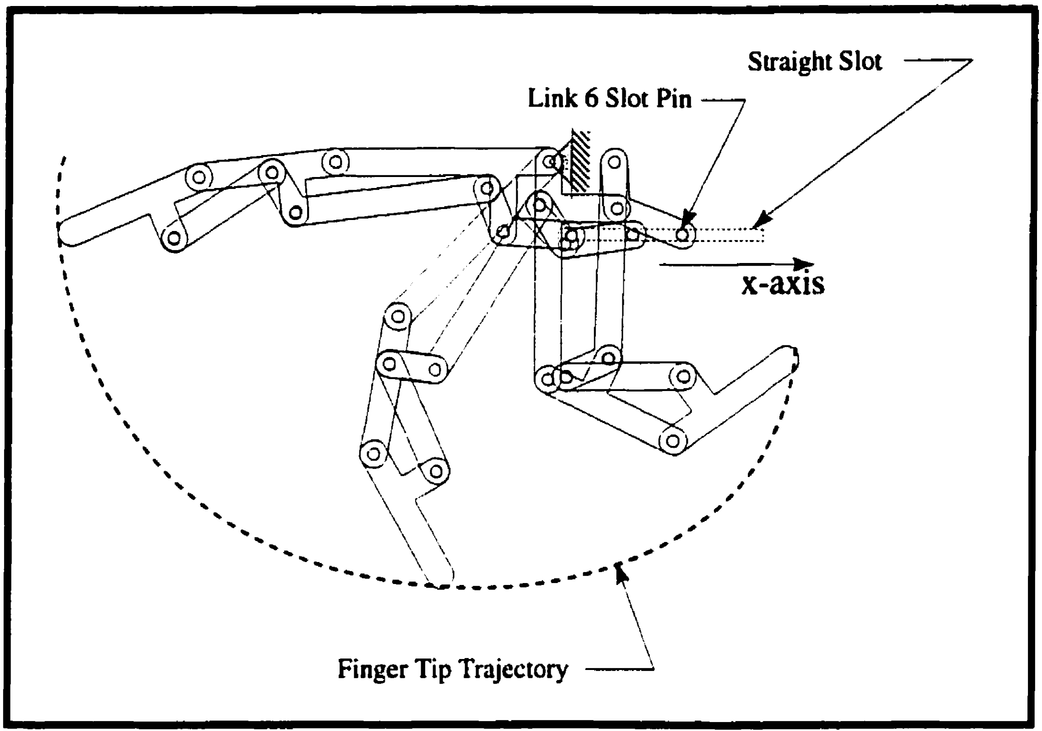


Figure 4.2 Finger Trajectory During Open or Close

Figure 4.2 shows three of the many possible positions of the finger during operation. They are, from left to right, maximum extended, an intermediate position, and maximum flexed. A dotted line represents the path that the finger tip travels through during extension or flexion. Because the finger has a single degree of freedom, no matter what type of object is encountered, the finger tips can only travel along this path. In order to achieve this full range of finger travel, the *Link 6 Slot Pin* can translate 13 mm in the x-direction within the palm, as shown. In order to keep the palm length to a minimum, it was important to minimise the translation distance of the *Link 6 Slot Pin,* and yet maintain the full range of motion.

Design and motion analysis of the finger was done using Working Model 2D(20) software. It helped to create a good finger tip trajectory, to minimise finger link dimensions, and to maximise the mechanical efficiency of the finger. This was not an easy task due to the number of variables, and the interrelations between the three parameters. For example, one of the compromises was between finger thickness (measured from the topside of a finger to the bottom side) and finger mechanical efficiency. The thicker the finger could be made, the better the mechanical efficiency. However, the thicker the finger became, the less useful it was for grasping tasks and the less cosmetic it was. Priority was placed on finger thickness over mechanical efficiency, since a thick finger design had more disadvantages. In addition, finger tip trajectory interfered with finger link sizing. Since trajectory was deemed most important, the medial phalanx of the finger was actually made shorter than anthropometrically normal. However, this shortening of the medial phalanx helped mechanical efficiency slightly. Hundreds of iterations were performed, leading to the final result. Final simulations showed that for every 6 N of force applied to the *Link 6 Slot Pin*, only 1 N became available as finger tip pinch force. Therefore, according to the simulations, the prototype hand was capable of producing a pinch force of about 31 N (7 lbf) to 35.6 N (8 lbf). Appendix A.2 shows some of these simulations.

The analysis with Working Model 2D software determined the link lengths required for the finger to meet the above criteria. Working Model 2D also revealed the amplitude and direction of the forces that each link would be subjected to during a pinch. In order to test whether the individual link designs could withstand these forces, a finite element software package called Ideas 5.1(22) was used to simulate the stresses within the finger links. In addition, Ideas 5.1 was useful in determining the thickness of the links to minimise their weight and size.

A virtual three dimensional model of each finger link was created with Ideas 5.1. The amplitudes and directions of the forces found during Working Model simulations, were then reprogrammed into the Ideas 5.1 finite element link models. Next, a solid finite element mesh consisting of 3000 to 12000 elements was created for each link. Aluminium 7075 T6, was selected from the Ideas 5.1 material database and used for the simulations. Simulation results showed the principal stresses and the shear stresses that would be experienced by the links under these conditions. Results showed that often, the most stressed area of the models was in the material around the pin joints. The principal stresses within the links were generally 10 times lower than the ultimate tensile strength of the material. The three dimmentional models, loading constraints, finite element mesh and simulation results, of *Link 1* and *Link 6* are shown as an example, in Appendix A.3. During subsequent machining of the fingers, the dimensions tested in Ideas 5.1 were strictly adhered to, often with some extra material left on, for good measure.

4.3 The Cylinder Spring Mechanism

The *Cylinder Spring* mechanism provides the adaptive grasp for the prototype hand. It allows each of the fingers and the thumb to be driven by the *Force Plate* and yet independently flex closed around an object. The *Cylinder Spring* system replaced the Spring Adaptive Grasp System, which had instability problems and was a pinch hazard. Figure 4.3 shows four of the *Cylinder Spring* mechanisms, connected to their respective *Link 6*, within the palm of the hand. The *Cylinder Spring* for the thumb, is not shown for clarity, but would be between the index and middle finger *Cylinder Springs*.

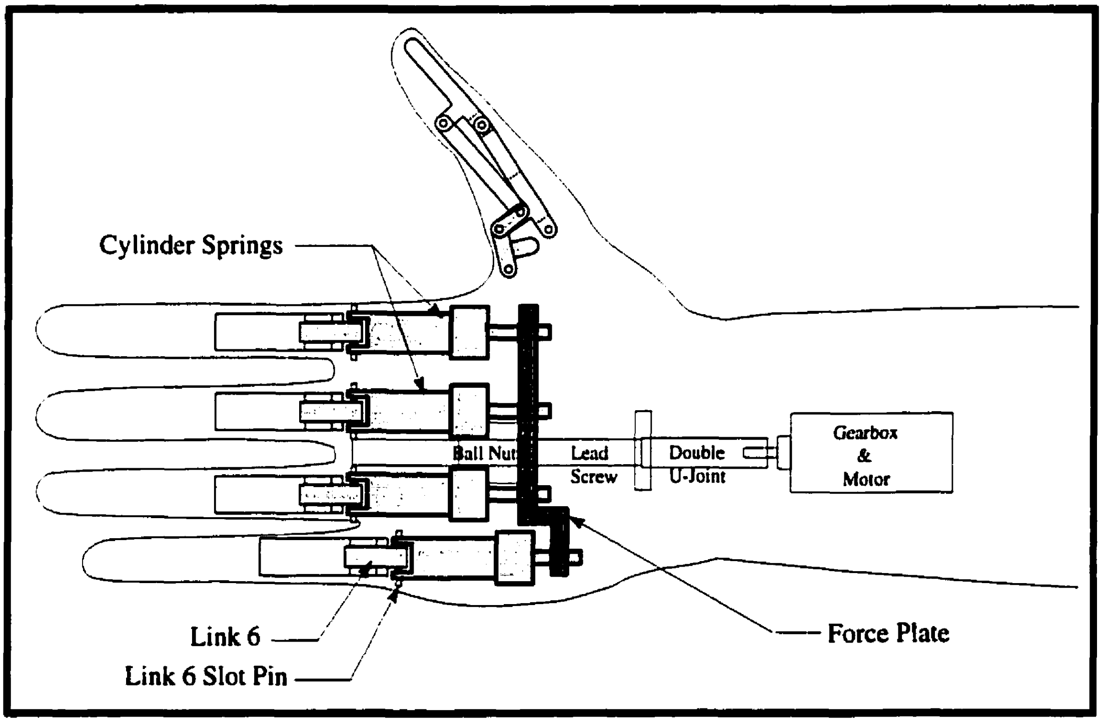


Figure 4.3 Cylinder Spring Adaptive Grasp System

Each *Cylinder Spring* is pinned to *Link 6* of a finger, via the *Link 6 Slot Pin*. This is the pin that rides in the *Straight Slot*, shown in Figure 3.5.

Figure 4.4 shows a detailed cross section of a single *Cylinder Spring*. The *End Cap* is threaded on the inside and screws onto the *Cylinder* which is threaded on the outside. The *End Cap* transfers the force of the *Piston*, via the *Compression Spring*, to the *Cylinder* body , during closure(flexion) of the hand. During opening(extension) of the hand, the *End Cap* has no purpose. The *Piston* has a thread on the far end, which is screwed into the *Force Plate*, thereby rigidly fixing the *Piston* to the *Force Plate*. When the *Force Plate* is pulled back or pushed forward via the *Ball Screw* assembly, the *Piston* moves back or forward. In this way, the force available at the *Ball Screw* is distributed to the five *Pistons* within the hand. The *Compression Spring* is loosely fitted over the *Piston*, such that it coils around the *Piston* shaft, as shown in Figure 4.4.

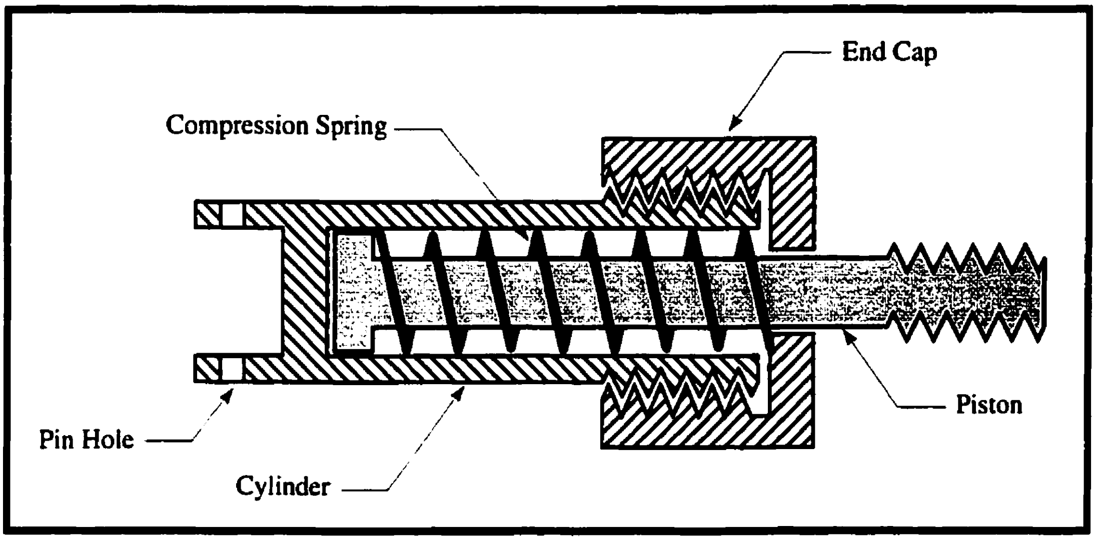


Figure 4.4 Cross section of Cylinder Spring mechanism

The inside diameter of the *Cylinder*, is large enough to minimise rubbing friction between itself and the *Compression Spring*. The *Compression Spring* within the *Cylinder* provides the adaptability feature of the hand. The spring constant, the uncompressed spring length, the fully compressed spring length and spring pre-compression are all very important parameters which influence the way in which the hand closes, the grasp forces achieved, and the energy consumed by the mechanism.

The *Cylinder Spring* has three distinct operating modes, as shown in Figure 4.5. In mode A, the *Compression Spring* remains uncompressed during operation. The *Compression Spring* is pre-compressed by a specific amount in mode A, so that the *Cylinder Spring* mechanism can transmit (i.e. transfer) a minimum defined force, without causing any deflection of the *Piston*. This force is transferred from the threaded end of the *Piston*, to the *Pinned Hole* on the *Cylinder*. In this prototype, the *Compression Spring* has a spring constant of 1.5 N/mm and can be compressed 14 mm (26 mm uncompressed, 12 mm fully compressed). The *Compression Spring* is pre-compressed by 2 mm, by the *End Cap*, which allows the *Cylinder Spring* mechanism to transfer up to 3 N of force without spring compression. This is roughly the amount of force necessary to overcome friction during the closure of a finger. During mode A operation, a finger will flex closed without any deflection in the *Compression Spring*. If the finger does not encounter any objects in its path, it will reach the fully closed position with the *Cylinder Spring* mechanism remaining in mode A.

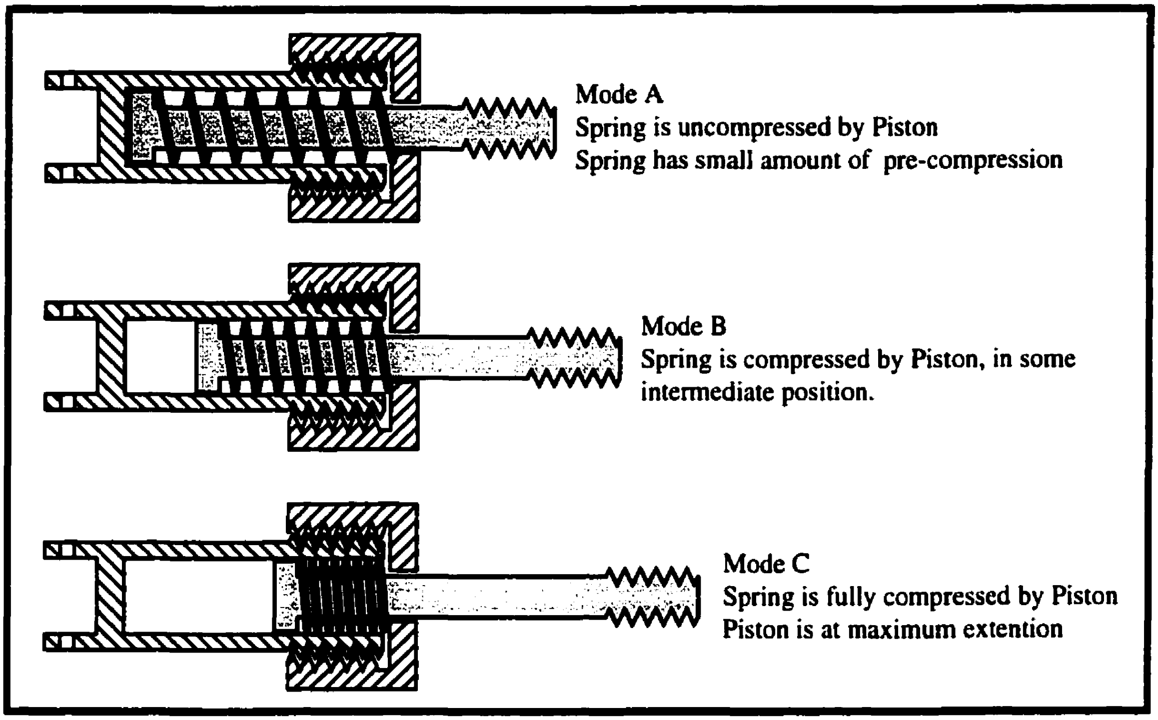


Figure 4.5 Different Operating Modes of the Cylinder Spring Mechanism

Mode B is any intermediate position between mode A, and mode C. In Mode B the *Cylinder Spring* mechanism can transfer an amount of force proportional to the compression of the *Compression Spring*. For example, if the *Compression Spring* is compressed 4 mm more than that of mode A, the *Cylinder Spring* mechanism can transfer (4 mm*1.5 N/mm+3 N=9 N) 9 N of force. If more force is transferred the *Compression Spring* will deflect a further amount. The *Compression Spring* can compress up to 12 mm in mode B, but beyond that amount, the mechanism goes into mode C operation.

In mode C, the *Cylinder Spring* mechanism is transferring enough force to fully compress the *Compression Spring*. Therefore, the *Cylinder Spring* is transmitting at least (12*1.5+3=21) 21 N of force and the *Compression Spring* cannot compress further. In mode C, the *Cylinder Spring* behaves like one rigid link, therefore all force is transmitted through the mechanism, to the fingers. Using Working Model software, it was found that during a normal tri-digital pinch, the *Cylinder Springs* of the index and middle fingers would need to transfer approximately 130 N of force each.

Figure 4.6 summarises the force that can be transferred through the *Cylinder Spring* mechanism during each of its modes of operation. This graph is based on the

Compression Springs actually used by the prototype hand. Up to 3 N can be transferred in mode A, 3 N to 21 N in mode B, and greater than 21 N in mode C. Only about one sixth of the *Cylinder Spring* mechanism force can be transformed into finger tip pinch force. Therefore, if the *Cylinder Spring* connected to the finger that is grasping an object, is in mode A or B, very little tip pinch force will result. The full force from a pinch is experienced shortly after Mode C is reached. During a pinch in which a finger tip exerts more than 4 N on an object, its associated *Cylinder Spring* must be in mode C.

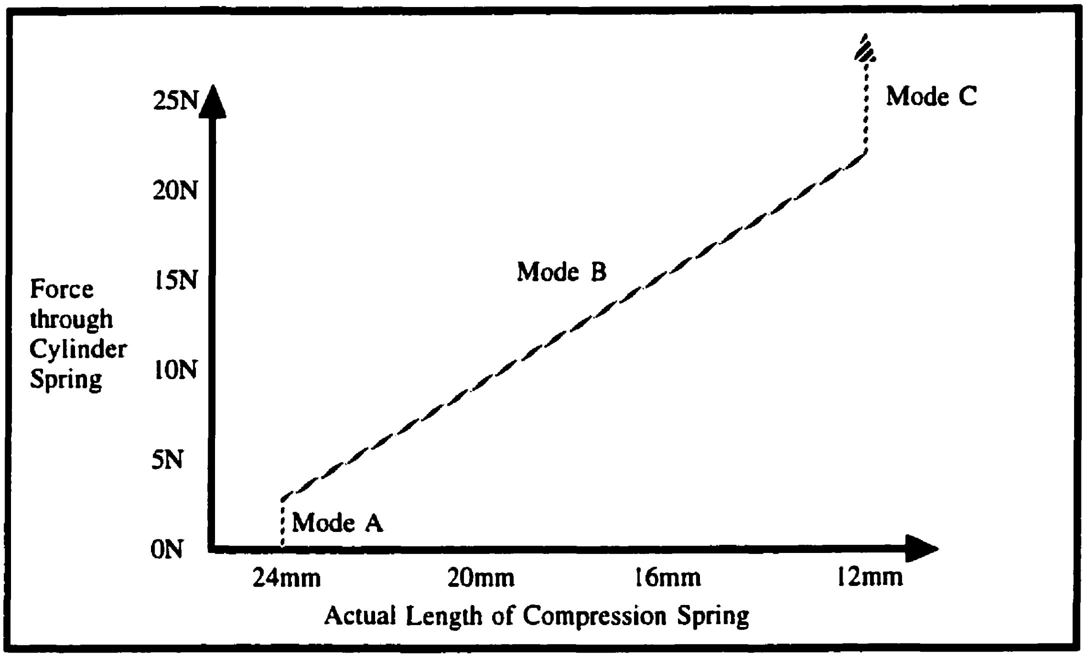


Figure 4.6 Force Transmission through Cylinder Spring Mechanism

4.4 Operation of the Cylinder Spring Adaptive Grasp System

The operation of the adaptive grasp system can now be described, given the description of the *Cylinder Spring* mechanism in Section 4.3. The external motions (fingers w.r.t. each other) and internal motions (*Cylinder Springs* w.r.t. each other) of the hand will be unique for every different object being grasped. In fact, even the same object can produce different configurations, depending on its position within the grasp. Factors that effect grasp and grasping force are: object size, shape, orientation, location in the hand and thumb position. All of these factors determine how far each finger will need to flex inward, to grasp an object. For example, some fingers may not contact the object at all during a grasp, due to the object's size and location in the hand, or due to the object's orientation.

The thumb position also influences the grasp configuration. The angle of the thumb with respect to the palm will determine which fingers (index or middle or both) will be in opposition to the thumb during a pinch grasp. During the grasp of smaller objects, this angle is important because some fingers will form a pinch, while the others flex completely. During the grasp of larger objects however, the thumb position is not as critical, since most or all of the fingers will be in opposition, due to the object's size. In some positions of the thumb, no fingers are in opposition. In this case, the hand is most likely performing a 'key' grasp.

The adaptive grasp is best described with an example of a typical tri-digital pinch. For this pinch, the thumb must be approximately perpendicular to the palm, which would centre it between the index and middle fingers. In this way the thumb opposes both fingers during closing. The object being grasped must be small enough or oriented in such a way that the remaining fingers do not contact it during closing.

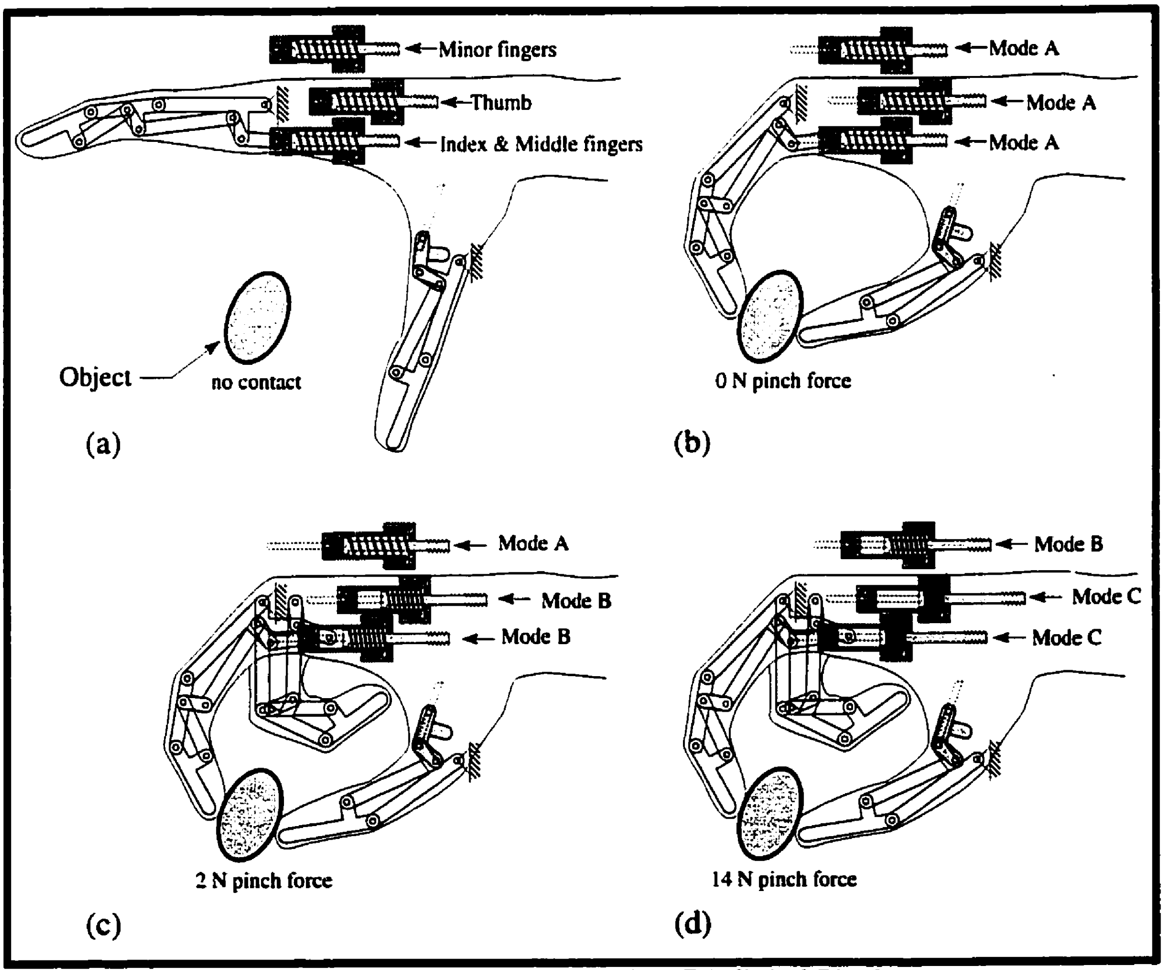


Figure 4.7 Operation of Adaptive Grasp During Tri-digital Pinch

Figure 4.7 shows the various stages during a tri-digital pinch. In the diagram, one *Cylinder Spring* is shown representing the operation of the index and middle fingers, one for the thumb, and one for the ring and pinky fingers. At first the hand will be fully open as shown in Figure 4.7(a). Here, all of the *Cylinder Springs* are in mode A, since no force is being transmitted.

Next, the hand closes down onto the object, as shown in Figure 4.7(b). In the process of closing, all of the fingers flex inward in unison. Only a small amount of force is necessary to flex the fingers inward. The force necessary is just enough to overcome the friction within the hand and is less than 3 N per finger, so all of the *Cylinder Springs* remain in mode A.

Next, with continued 'pull' from the *Force Plate*, as shown in Figure 4.7(c), the two minor fingers continue to flex inwards, since there is no object in their path. Also, their *Cylinder Springs* remain in mode A. The index finger, middle finger and thumb however, have all made contact with the object and cannot flex inward further. Their *Cylinder Springs* 'absorb' the motion of the *Force Plate*. These *Cylinder Springs* are now in mode B. The compression springs inside are compressed and some amount of force is transmitted to the object. While these *Cylinder Springs* are in mode B, the object will experience only 0 N to 4 N of pinch force. This is just barely enough pinch force to keep the object stable. While the hand is in the operational stage of Figure 4.7(c), it has not completed a firm grasp, and objects within the grasp may become unstable.

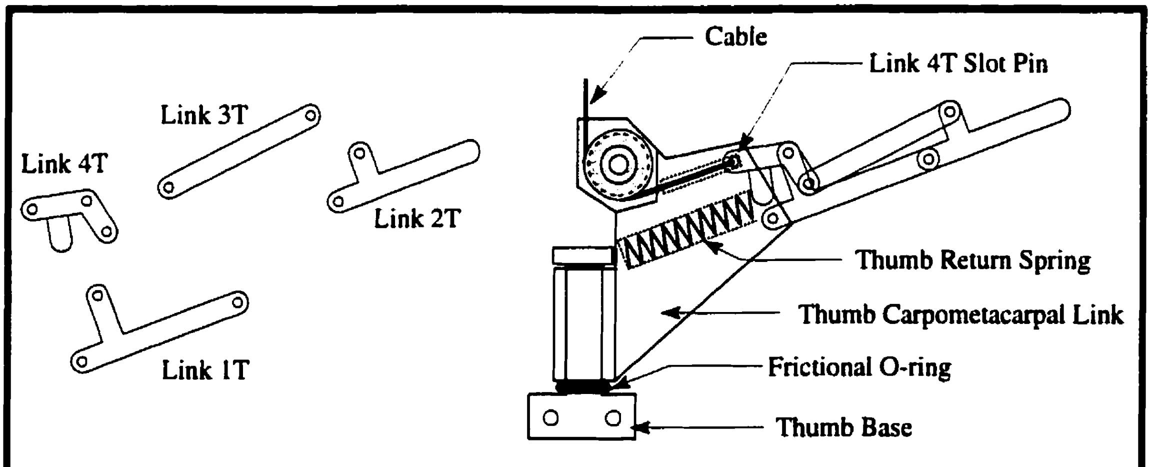
Finally, continued 'pull' from the *Force Plate* leads to the final grasp configuration shown in Figure 4.7(d). Although the diagram of the hand is identical to Figure 4.7(c), the *Cylinder Springs* within the palm have changed modes. The index and middle finger *Cylinder Springs* are now both in mode C, and the *Cylinder Spring* of the thumb is also in mode C. Since a *Cylinder Spring* in mode C can no longer deflect its *Piston*, it behaves as a rigid link, bringing all motion in the hand to a stop. Maximum pinch force is now exerted on the object, since all of the force from the *Force Plate* is transferred directly into the fingers and thumb.

Theoretically, the first *Cylinder Spring* to reach mode C should bring the adaptive grasp system to a stop. This is the case when the thumb is rotated outward far enough that it does not oppose any fingers. However, the thumb usually opposes one or more fingers during a grasp, therefore, a positional equilibrium is always reached where the *Cylinder Springs* of both the thumb and at least one finger reach mode C. This forms a bi-digital pinch. In some cases, like the previous example, the thumb is centred directly between the index and middle fingers. During a pinch the *Cylinder Springs* of both these fingers reach mode C and therefore a tri-digital pinch can be formed. This will only occur, however, if the amount of flex of the index and middle fingers is almost identical.

In summary, the adaptive grasp system of the prototype hand makes use of the *Cylinder Springs* which 'absorb' the motion of the *Force Plate*, when their respective finger has encountered an object. This allows the other fingers to keep flexing inwards. During the start of a grasp, all *Cylinder Springs* are in mode A. Next, the *Cylinder Springs* of any fingers making initial contact with an object go into mode B. These fingers exert a light amount of tip pinch force while their *Cylinder Springs* are in mode B. Finally, as the grasp continues, the first finger with a *Cylinder Spring* that reaches mode C, in addition to the thumb *Cylinder Spring*, stops all motion in the hand. These two digits will create a pinch that will carry approximately 80 percent of the grasp force. All remaining *Cylinder Springs* will be in mode B. If there is a 'tie' between two fingers in approaching mode C, then both fingers will reach mode C and a tri-digital pinch will be formed.

4.5 Thumb Design

The thumb of the prototype hand is based on a design very similar to the fingers. The thumb however, has only two phalanges that can flex and extend, the metacarpophalangeal and the distal interphalangeal, shown as *Link 1T* and *Link 2T* respectively in Figure 4.8(a).

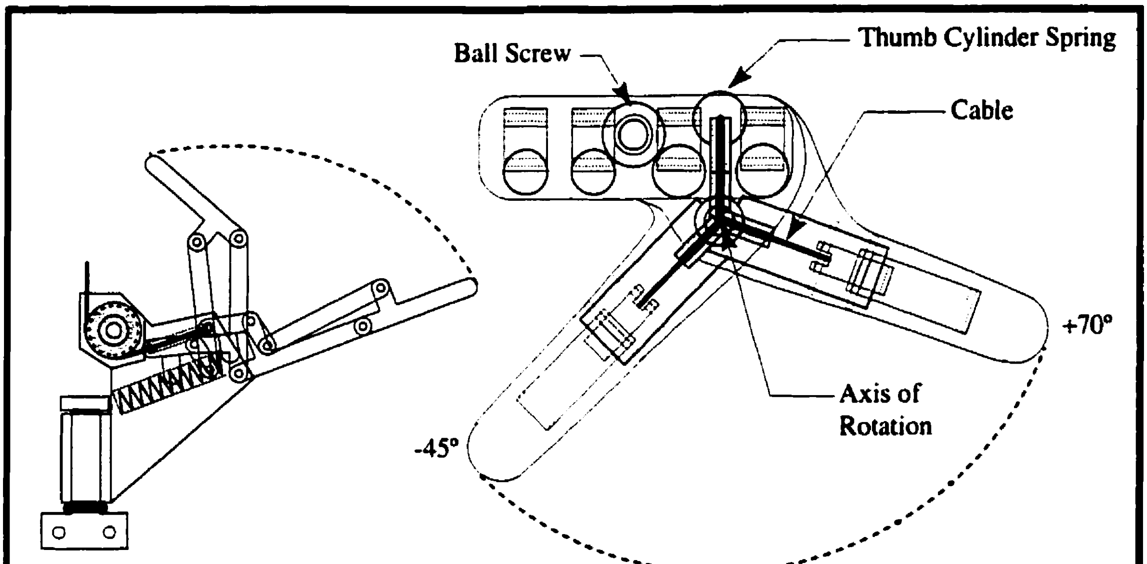


(a) dismantled Thumb Links (b) Assembled Thumb

Figure 4.8 Thumb Links and Assembly

It was observed that during most grasps with the natural hand, the carpometacarpal bone in the thumb would flex or extend a very small amount with respect to the palm. During abduction and adduction of the thumb, it was noticed that most of the motion took place by the rotation of the carpometacarpal bone. Hu(23) created a prosthetic design with a thumb that could adduct and abduct, and found that such a two degree of freedom thumb could provide better function and cosmesis. Therefore, a thumb capable of two degrees of freedom was also built into the prototype hand.

When creating these motions, it was decided that the *Thumb Carpometacarpal Link* in the prototype hand would not flex or extend, but only adduct and abduct. This allowed for a much simpler mechanism and left room in the palm for the adaptive grasp system. Thumb flexion is created by 'pulling' on the *Cable* shown in Figure 4.8(b). This *Cable* is attached to the *Link 4T Slot Pin*, which travels in a straight slot. This pin is in turn attached to *Link 4T*, which drives the motion of the remaining links in the thumb. Because the thumb is driven by a *Cable*, the *Thumb Return Spring* is needed to extend the thumb, when the tension on the *Cable* is relieved. The axis that the *Cable* is 'pulled' along is designed to coincide with the axis of rotation of the thumb. This allows for thumb rotation, without the possibility of the cable slipping off the pulleys, as shown in Figure 4.9(b).



(a) Flexion and Extension (Bottom View)

(b) Adduction and Abduction (Front View)

Figure 4.9 Thumb Range of Motion

Figure 4.9(a) shows the flexion and extension range of motion of the thumb. A dotted line is shown representing the thumb tip trajectory. This flexion and extension can be performed independently of the thumb rotation shown in Figure 4.9(b), and vice versa.

Adduction and abduction of the thumb is achieved manually by the user of the prototype hand. A recent survey of amputees(1) has shown that most amputees have an able natural hand. After learning to use the prototype hand, it is hoped that the experience and personal preference of the user will dictate which rotational position of the thumb is useful for particular grasps. The user would be able to rotate the thumb to that position with his natural hand. The original design of the prototype hand allowed for three distinct thumb rotational positions, but that design was abandoned. It was felt that a thumb with variable positions could be more functional, after a number of discussions with staff at Bloorview MacMillan Centre. The multi-position design is achieved by the addition of a *Frictional O-ring*, as shown in Figure 4.8(b), which is 'squeezed' in place by tightening a bolt on the back of the *Thumb Base*.

4.6 Selection of Ball Bearing Lead Screw

The operation of the adaptive grasp system and the operation of the fingers is based on the principle of linear motion. The *Force Plate*, to which the fingers are connected via the *Cylinder Spring* mechanisms, was designed to translate forward and backward within the palm. Since the motor only provides torque as a mechanical output, the easiest way to convert the torque into a linear load is with the use of a lead screw. Two types of lead screws were considered. One was a conventional screw with a plastic nut and the other was a ball screw with a ball bearing nut. The applicability of both systems was discussed with the supplier(24,25) and it was decided that a ball bearing lead screw would be the only acceptable screw to use.

The problem with the plastic nut lead screw was that the efficiency of that combination was very low. The prototype hand needed a screw as small and lightweight as possible. In order to increase the efficiency of a plastic nut lead screw, a greater number of starts would be necessary on the shaft and the lead would have to be increased greatly. The most efficient plastic nut lead screw in the 1/4" to 3/8" diameter range was still only 41 percent efficient. Unfortunately, the higher the lead, the easier it would be to 'back drive' the screw, which would necessitate the addition of an anti-rollback mechanism within the prototype hand, thereby complicating the mechanism and adding weight. To prevent 'back drive' the selection guide recommended that the lead of the screw be less than one third the shaft diameter. The advantage of the plastic nut lead screws is that they are fairly inexpensive.

The solution was to use a ball bearing lead screw, which has an efficiency of 90 percent or higher. An MRB0601 ball bearing screw was selected with a 6 mm diameter shaft and a 1 mm lead. Because of its high efficiency, it was possible to 'back drive' this unit before it was installed. However, after it was installed within the prototype hand, the additional friction within the hand's mechanisms prevented any 'back drive'.

4.7 Wrist Design & Motor Placement

One of the objectives of the prototype hand design was to keep the palm as slim as possible. There have been complaints regarding the cosmesis of the conventional VASI hand prostheses, in that they look too 'fat or thick'. One way in which to keep the palm slim, is to place the motor just behind the wrist in the forearm. This possibility was proposed to the staff at Bloorview MacMillan Centre and discussed. It was generally agreed that a large number of amputees often had at least 2 to 3 inches of space up to where the wrist would normally be on their stump. Therefore, placing the motor within the forearm of the prototype prosthesis would be an acceptable design for a majority of users.

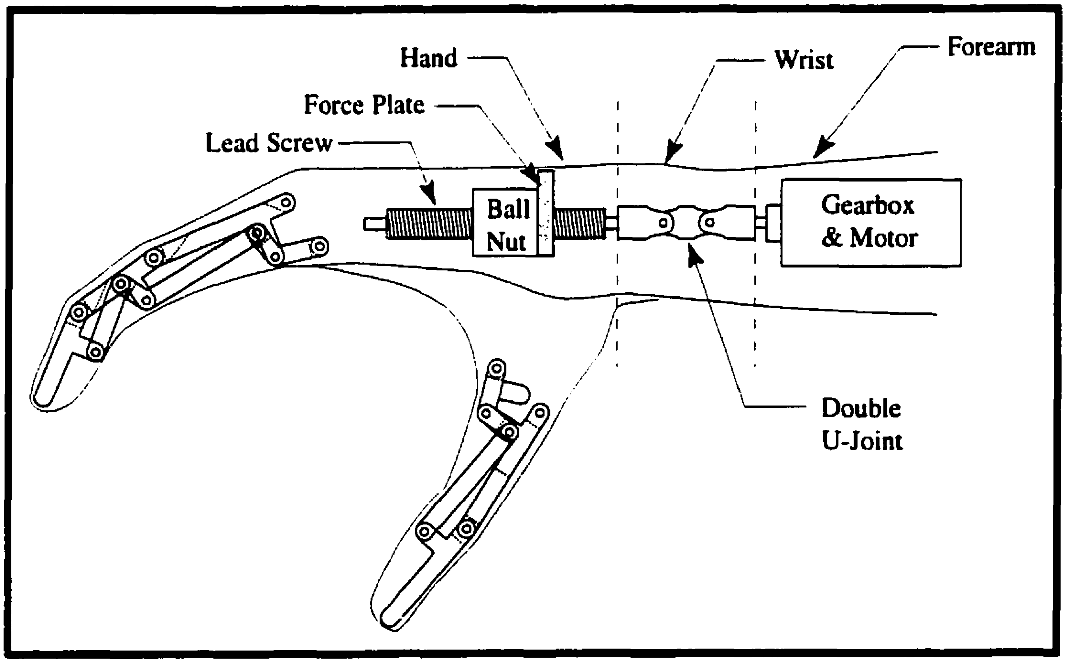


Figure 4.10 Motor Location within Prosthetic

If the wrist unit being used with the prototype hand can only rotate, the connection to the motor would be a straight shaft, co-axial with the axis of rotation of the wrist unit. However, a wrist unit that can only provide rotation forces the user of a prosthesis to make many compensatory body motions to line up the hand with an object. A more favourable type of wrist unit would provide flexion, extension, adduction and abduction in addition to rotation. Such a wrist design would have three degrees of freedom and would most likely take the form of a ball and socket unit. In order to connect the motor output to the ball bearing lead screw through such a ball and socket wrist unit, the use of a u-joint would be required. Such a system is shown in Figure 4.10. In order to work effectively, a hole would be made in both the ball and socket, to allow the u-joint to pass through the centre. A double u-joint has been chosen for this application for two reasons. Firstly, a double u-joint can function very well even if the output axis is rotated up to 60° away from the input axis. Most single u-joints will function only to 30°. Secondly, a double u-joint provides constant speed from the input end to the output end, at all times. A single u-joint does not do this whenever the output axis is tilted away from the input axis.

The motor chosen for the prototype hand is a MicroMo 1724E. It is equipped with a gearbox with a ratio of 22:1. The specifications of the motor and the calculations used in selecting it are listed and shown in Appendix D. The gearbox supplies the lead screw with up to 112 Nmm (15.9 oz-in) of torque. This translates into approximately 540 N available for 'pull' work by the Force Plate, when frictional losses are taken into account. The motor, gearbox and double u-joint are 80 mm (3.2 inches) long all together. This should be able to fit within the forearm of the prosthesis, without adding any unnatural length to a majority of users. The double u-joint selected is a standard off the shelf unit that takes up 45 mm of the length. With the design of a custom double u-joint, this length could probably be reduced down to 30 mm or less.

4.8 Control & Power for the Prototype Hand

The prototype hand is controlled with a system that is identical to the one used by conventional VASI prosthetic hands. It is the VASI 5-9 B proportional controller, which can vary the speed of the motor depending upon the intensity of the signal received from the electrodes. Two EMG electrodes are used, one for the flexion signal and the other for the extension signal. This can provide some control over the speed of the hand flexion or extension. The controller uses pulse width modulation (PWM) to control the speed of the motor. This system is effective at maintaining high torque at low speeds. A conventional Otto Bock 300 mAh battery is used with the VASI control system. It consists of five 1.2 Volt nickel cadmium cells to provide 6 Volts.

Chapter 5

Mechanical Review of the Prototype Hand

5.1 Overview

This chapter reviews the mechanical attributes of the completed prototype hand. The construction details are reviewed, along with any potential problems. Also, recommendations are made as to how these specific problems could be corrected in any subsequent versions of the hand as currently designed. A set of diagrams of the hand's major components and materials used, are provided in Appendix C. A total cost breakdown for the prototype hand is also included.

All of the components of the prototype hand, with the exception of prefabricated parts, were machined by the author. There were two main reasons for this. Firstly, by machining the parts, there was better control over the design. Improvements to the design or unforeseen problems, that were spotted during fabrication, could be carried out or corrected immediately. Secondly, there was a cost savings. The prefabricated parts used in the prototype were the lead screw, roller bearings, roll pins, springs, the cable and the motor and gearbox. However, many of these items were also modified by machining, to make them fit within the design.

5.2 The Fingers

During simulations with Working Model 2D software, the finger links were able to pass through each other, on the two-dimensional plane, for the purposes of the analysis. In some cases, three of the links would occupy the same area in two-dimensional space. In the real world however, link to link penetration is impossible. Therefore, the fingers had to be built in such a way that they would not collide with each other. One method was to have the links functioning on three adjacent parallel planes. However, this design would have created a high moment in the pins, perpendicular to the flexion/extension plane of the finger. To allow for even loading of the pins in joints, a symmetrical design of links within links was built. The details of this design for the fingers are shown in Appendix C.1.

The links comprising the fingers were machined from 7075 T6 aluminium. This standard grade of aluminium was chosen for its low cost, low weight and high strength. It was also very easy to machine and could be machined with no lubricant. The aluminium fingers that were machined for the prototype hand were sized within 2 percent of the original design drawings. The four assembled fingers are shown in Figure 5.1.

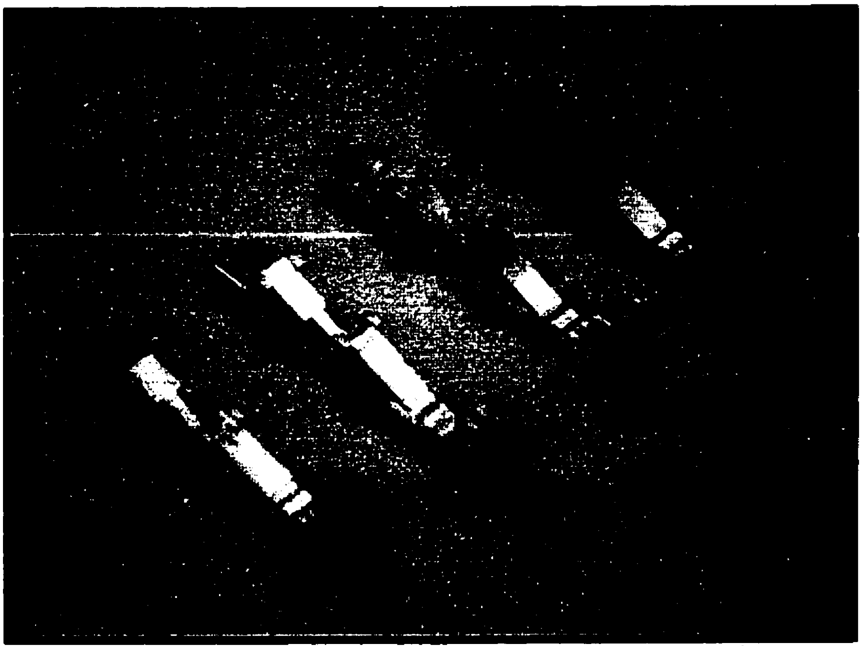


Figure 5.1 Aluminium Fingers of the Prototype Hand

One of the difficulties encountered during the construction of the fingers was how to properly pin the finger links together. Hardened steel pins of 1.588 mm (1/16 in) diameter were initially used, with 'push on' nuts, fastened to each end of the pins. In order to use these 'push on' nuts, 2 mm of the pin had to protrude out from each end of the joint. This created a problem because all these protruding pins reduced the useful space between the fingers and would have shredded a conventional PVC glove during operation. A pin that would not protrude from the fingers and yet remain in the joint without falling out was needed. A roll pin could provide this function and was adopted for the design. When creating a revolute joint with a roll pin, the hole in one of the links must be small enough so that the pin will be 'jammed' in tightly and the hole in the other link must be large enough so that the roll pin can rotate loosely within it. Unfortunately, due to limitations in the sizes of drill bits available, the hole that was to be 'larger' was machined three thousandths of an inch too large. This resulted in a small amount of slack in each finger joint. As a result, the combined slack of all the joints was almost 3 mm at the tip of each finger. It is recommended that future versions of the fingers use a hole that is one thousandth of an inch larger than the smaller hole when using a roll pin, to decrease the amount of slack in the finger.

Finger slack does not affect the operation of the prototype hand, nor does it take away from the final pinch force. In fact, it has a couple of advantages. Firstly, when the glove was worn, the slack makes the fingers appear more natural as the finger tips can deflect very slightly as the hand bumps into objects, or is drawn across a bumpy surface. Secondly, the loose fit of the pins within the many holes of finger links greatly reduces the overall friction of the finger. This allows the hand to flex and extend the fingers with less energy, thereby increasing the battery life. However, one disadvantage of slack is that it would make it impossible to implement a tactile sensor system capable of detecting slip, or an actively controlled pinch force system. Slack would have to be virtually eliminated to implement these systems.

One of the specifications for the fingers required that a compliant material be placed on the inside surfaces of the fingers and palm. Joiner(26) had made this recommendation for the tips of fingers and had shown that better grip stability could be achieved with this method. For the prototype hand, aquarium grade silicone was used to provide this compliance. It was applied to the under side of the finger tip link, *Link 4* and *Link 5*. After the silicone cured, the excess was cut away with a razor blade, to form the desired shape. Silicone naturally bonds very well to aluminium and even after many trials of pull out tests, the silicone remained bonded to the aluminium exceptionally well on most links. Aquarium grade silicone was used because it is one of the few grades of silicone that is lead free.

5.3 The Cylinder Spring Mechanisms

An important consideration during operation of the *Cylinder Springs* is to keep the *Piston* axis coaxial with the *Cylinder* axis. Referring to Figure 4.4, it is important to minimise the contact between the tip of the *Piston* and the inside wall of the *Cylinder*. Each of the *Pistons* is rigidly fixed to the *Force Plate*, thereby fixing the distance between the axis of each *Piston*. This centre to centre distance must also be maintained by the *Cylinders* which slide within the channels of the *Palm*. The axis of the lead screw must also be parallel to the axis of the *Pistons*. If there is any misalignment between these elements, rubbing friction will result. The greater the misalignment the greater the rubbing friction.

To minimise misalignment, care must be taken during machining of the parts. This includes not repositioning the parts on the milling machine, until all critical holes are drilled or all channels milled. All of the required pieces for the prototype were machined as well as possible, however some misalignment still occurred. The mechanism was able to 'wear' into a smooth action after several hundred cycles. If the machining is not done correctly, the wear could become excessive or cause the parts to fail prematurely. Figure 5.2 shows the *Cylinder Springs* within the *Palm*.

The *Compression Spring* that was used, fits loosely around the *Piston* and slides loosely within the *Cylinder*. Because the spring used was a standard variety, the *Piston* diameter was turned down on the lathe, as necessary, for the loose fit. The bore diameter of the *Cylinder* was similarly chosen.

The *Cylinder Spring* mechanisms were machined from the same aluminium as the fingers. The detailed diagrams of the *Cylinder Springs* are shown in Appendix C.2.

Figure 5.2 Cylinder Springs within Palm

The *Cylinder Springs* are attached to the fingers via the *Link 6 Slot Pin*, as shown in Figure 4.3, and as can be seen in Figure 5.2. This pin also simultaneously rides in the *Straight Slot* which is machined into the channel within the *Palm*. The pair of slots that comprise one '*Straight Slot*' in this design must have their mutual axes coaxial with the axis of the *Piston* for smooth travel of the *Cylinder Spring*.

At the other end, the *Piston* of the *Cylinder Spring* is threaded with a 8-32 UNF thread. Here, the *Pistons* are screwed in to the *Force Plate*. This is a very important design feature. When the prototype hand is assembled, the tips of the fingers may not line up with each other. That is to say, each finger may have a different starting extension than the others. This may occur due to dissimilar *Compression Spring* lengths, machining problems or wear. In order to line up the finger tips, the *Pistons* can be 'screwed' forward or backward within the *Force Plate*. This forward or backward adjustment will flex or extend the finger slightly to adjust its starting position.

5.4 The Thumb

The metacarpophalangeal and distal interphalangeal links of the thumb were built and operate in the same way as the finger links, except for the different dimensions. The *Thumb Carpometacarpal Link*, as shown in Figure 4.8(b) is the main difference between the thumb and the fingers. It has been machined out of Delrin plastic. Appendix C.3 shows the dimensioned thumb links. Figure 5.3 shows the actual assembled thumb, with an acrylic *Thumb Carpometacarpal Link*, so that the internal *Thumb Return Spring* is visible.

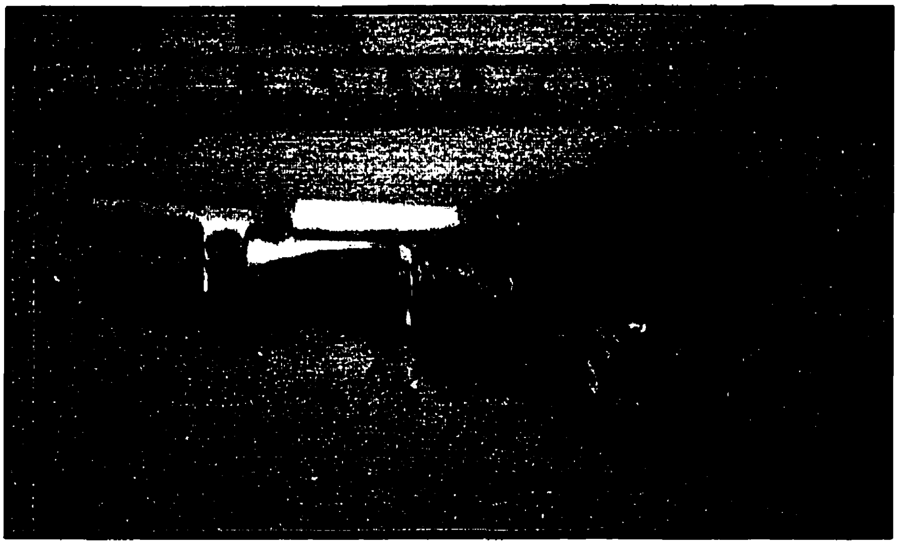


Figure 5.3 Assembled Thumb with Acrylic Carpometacarpal Link

There are four primary functions of the *Thumb Carpometacarpal Link*. Firstly, it has a *Straight Slot* machined into it, in which the *Link 4T Slot Pin* must travel to create the proper flexion/extension motion for the thumb. A hardened steel pin is used for the *Link 4T Slot Pin*, with 'push on' nuts located at each end to keep the pin from slipping out during operation. Unfortunately, this causes the pin to protrude out by 2 mm past the body of the *Thumb Carpometacarpal Link* on both sides. The cable used to actuate the thumb loops over the *Link 4T Slot Pin*. The loop is formed by tying a knot in the cable, close to this pin. Initially this knot would constantly unravel. After much trial and error, a method of tying a knot that would not slip, even with very high tension, was developed. Nevertheless, a better way of securing the cable to the *Link 4T Slot Pin* must be developed.

Secondly, there is a pulley located at one end of the *Thumb Carpometacarpal Link* around which the cable passes. The job of this pulley is to line up the cable axis with the *Straight Slot* on the *Thumb Carpometacarpal Link* at one end, and to line up the cable axis with the axis of rotation of the *Thumb Carpometacarpal Link* at the other end. Regardless of the angle of the thumb mechanism with respect to the palm, the cable must always be lined up at both ends, to prevent it from slipping off the pulley. This was shown in Figure 4.8(b).

Thirdly, the *Thumb Carpometacarpal Link* must house the *Thumb Return Spring* which is needed to return the thumb to the extended position when the tension in the cable is relieved. The spring sits within a hole drilled parallel to the *Straight Slot.* It can be seen clearly in the centre of the *Thumb Carpometacarpal Link* in Figure 5.3. *Link 4T* of the thumb has a small protruding 'arm' that compresses the spring as the thumb flexes closed. When tension in the cable is relieved, this spring extends the thumb by pushing back on the 'arm' of *Link 4T.* One of the difficulties in implementing the design was that there was no lateral support for half the spring at the *Link 4T* end. The spring would buckle when pressure was exerted on it, rather than compress. This was corrected by placing a short '*Piston* like' element within the spring, so that it could not buckle when compressed with an off centre load.

Lastly, the main purpose of the *Thumb Carpometacarpal Link* is to rotate the entire thumb so that it can simulate the adduction and abduction of the natural thumb. The *Thumb Base* link is machined from 7075 T6 aluminium. It is rigidly connected to the end of the *Palm* by two bolts. Protruding out of the *Thumb Base* is a round shaft, overtop of which the *Thumb Carpometacarpal Link* rotates. Through careful design, the axis of this shaft is coaxial with the axis of the cable emerging from the front of the *Palm.* In this way, no matter how the thumb is rotated, the cable will never slip off the pulleys. Currently the thumb design uses a *Frictional O-ring* at the base to keep the thumb in position after it is rotated. This is a recent addition to the design and it is expected that the O-ring will wear quickly. Another material should be selected that will provide high friction, but will wear more slowly. The material does not have to be an O-ring in shape but could be in the form of a washer. Regardless, any frictional material will wear and the compression upon the material will have to be adjusted a multiple number of times during the year. The only way to avoid this would be to use a thumb with three distinct positions as originally proposed. This would involve a spring loaded ball located in the *Thumb Carpometacarpal Link*, pressing into three distinct grooves located on the shaft. However, it is felt that a three position thumb is not as functionally useful as a variable position thumb. A more careful redesign of the thumb position locking system must be made.

5.5 The Palm & Lead Screw

The *Palm* was machined from a solid block of Delrin plastic, which has proven to be exceptionally strong and resistant to wear after many cycles of the prototype hand. Appendix C.4 shows the dimensions of the *Palm*. Figure 5.4 shows the back of the *Palm*.

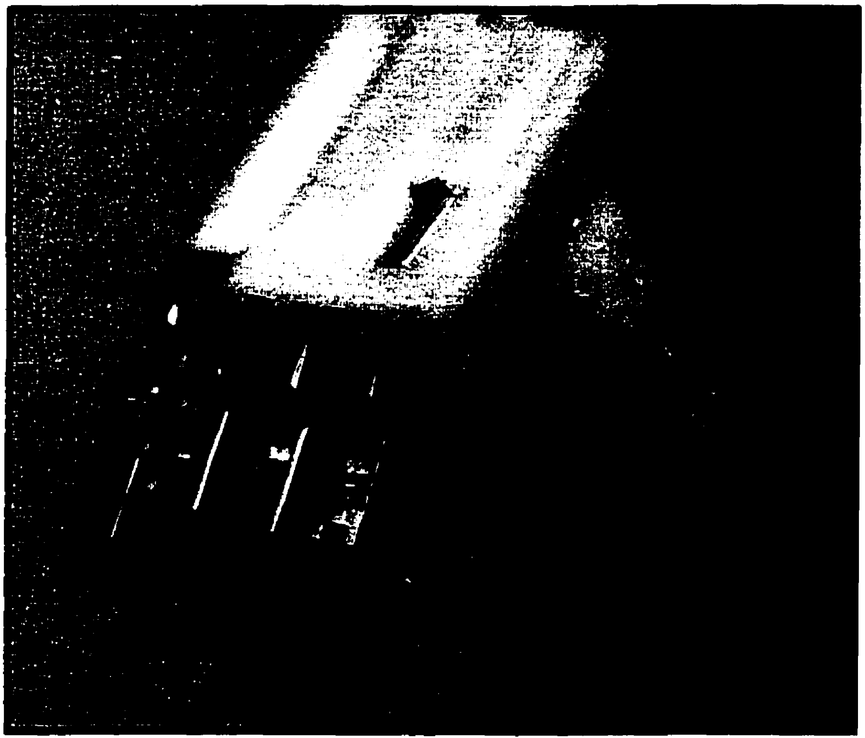


Figure 5.4 Prototype Hand Showing Back of Palm

There were three primary concerns when creating the *Palm*. One of these concerns was to keep the *Channels* and the *Straight Slots* as parallel as possible to the *Cylinder Springs* and the *Lead Screw*. The importance of this was to minimise the internal rubbing friction of the mechanisms, as described in Section 5.3.

The next concern for the *Palm* was the overall weight. A careful balance was reached between strength and weight. There were many high forces occurring within the prototype hand and the *Palm* acted like the ground link for many of these. Areas of concern were the support points for the *Lead Screw*, the *Thumb Base*, the forces of the *Link 6 Slot Pins* on the *Straight Slots* and the pin forces from the *Link 1* links. In addition, it was desirable to create a 'shell' that could house the mechanisms within and could be sealed to keep out dirt and debris. The back of the *Palm* was machined down in many areas to reduce the average *Palm* thickness. All sharp edges were milled down at angles to give the *Palm* a more rounded, natural appearance and to prevent tearing of the glove.

The last concern for the *Palm* was the path which the cable ran through. It was extremely difficult to design a path that would not interfere with the other mechanisms. One of the major problems was placing the two small pulleys located between the index and middle fingers at the front of the *Palm*. Initially, this was expected to be a single pulley of approximately 10 mm diameter, or larger. This diameter was necessary because it matched the minimum radius of curvature of the Kevlar cable being used. Unfortunately, in order to line up the tangent of the pulley with the axis of rotation of the *Thumb Carpometacarpal Link*, the pivot point of the pulley would pass through the *Straight Slot*. This would cause interference problems with the *Link 6 Slot Pins*. In order to make the system work, two smaller pulleys were used which were pivoted above and below the *Straight Slot*. However, the minimum radius of curvature for the cable was not met with these smaller pulleys, which were only 6 mm in diameter. There have been no signs of cable wear at these locations, even though the cable has failed by breaking, on two occasions thus far. The two failures were attributed to the previous set screw connection system employed at the thumb *Cylinder Spring*, which caused damage to the cable during the securing process. It is recommended that the two small pulleys be replaced by a redesigned single pulley system. This could be done by making the pulley protrude out from between the index and middle finger further than it currently does, but this might detract from the hand's cosmesis.

5.6 The Wrist and Double U-joint

The ball wrist unit that was proposed for the prototype hand was not built. The design of the ball wrist would have taken a substantial effort. The ball wrist was a whole design in itself, complete with a frictional locking system to immobilise the wrist when necessary. Although this wrist would greatly improve the functionality of the prototype hand, there was not enough time to undertake such a design. A standard ball and socket wrist would not be appropriate for the prototype hand because a double u-joint must be able to pass through the centre. As such, a custom version must be designed specifically for the prototype hand. Currently, a Delrin attachment is bolted to the end of the *Palm*, to hold the motor rigidly in place with respect to the *Palm*. As it is currently built, the design would be appropriate for a rotational wrist only.

The importance of the double u-joint has diminished in this design, since the ball wrist was not incorporated. Nevertheless, a double u-joint was initially installed between the motor and the lead screw. One major problem was uncovered during this trial.

The double u-joint selected was a lightweight, Delrin plastic version, part # A 5Z 8-DD204 from a catalogue(32). The maximum torque that could be transmitted by this double u-joint was 40 oz-in, which was about half the application torque. Therefore, this u-joint was used, however, it eventually failed during operation.

The problem was the method of securing the double u-joint to the motor at one end and to the *Lead Screw* at the other. The Delrin attachment that held the motor in place was not perfectly rigid and as the motor spun, it flexed slightly. This flexion compressed and extended the u-joint very slightly. In addition, the *Lead Screw* was secured only by needle roller bearings, which cannot support a thrust load. (A brass washer within the palm supported the major thrust load during hand flexion) As a result, the *Lead Screw* would shift axially by up to 1 mm depending on the direction of operation. This further compressed and extended the double u-joint. The extension of the double u-joint was not a problem, because the three links that comprised it remained in line with each other and the operation was smooth. However, when the double u-joint was put under compression, the central link shifted out of axial alignment, to take up the compression. This caused the double u-joint to operate improperly and noise could be heard from the device. This cyclic loading seemed to have caused a high strain on the pins, which was where the device failed. It is recommended that future designs of the prototype hand incorporate thrust bearings for the *Lead Screw*. This will keep the *Lead Screw* from travelling axially, which was the major cause of the double u-joint problems. Unfortunately, thrust bearings that were small and strong enough for the prototype hand application were hard to find.

5.7 The Gearbox and Motor

The gearbox that was selected for this design was the MicroMo 16AK 22:1 gearbox. It was a plastic gearbox with brass gears and had the output shaft supported by a ball bearing. Because it was plastic, it had a weight of only 4 grams. The specifications for this gearbox showed that it was recommended for a maximum output torque of 100 Nmm (14.2 oz-in) during intermittent use. The prototype hand would create a torque of 125 Nmm (17.66 oz-in) during the final stages of a pinch. This problem was discussed with the one of the applications engineers of MicroMo. He mentioned that for the purposes of a prototype, the gearbox would be sufficient and would most likely last for a long period of time. He noted, however, that transient torques, that would occur during electrical current peaks could reach as high as 141 to 170 Nmm (20 to 24 oz-in) of torque. For an actual application, he suggested the use of a planetary gearhead with a metal case. These gearboxes were capable of an output torque of up to 450 Nmm (63.8 oz-in), however, their weight was approximately 30 grams. Lastly, he mentioned that MicroMo was working on a plastic case for the planetary gearhead. It should be determined if this new gearhead is available.

Currently, the motor and gearbox assembly generates a substantial amount of noise during use. This noise level would not be acceptable for a prosthetic device. It is suspected that because the current gearbox is being pushed to the limit, it is generating this noise. The hand mechanisms themselves have very low noise, which is surprising considering this is the first iteration of the prototype hand. It is recommended that the source of the noise be determined and reduced in level.

5.8 Summary

The mechanical attributes of the working prototype hand have been presented and problem areas identified in a thorough manner. These are the major areas that still require correction in the prototype hand.

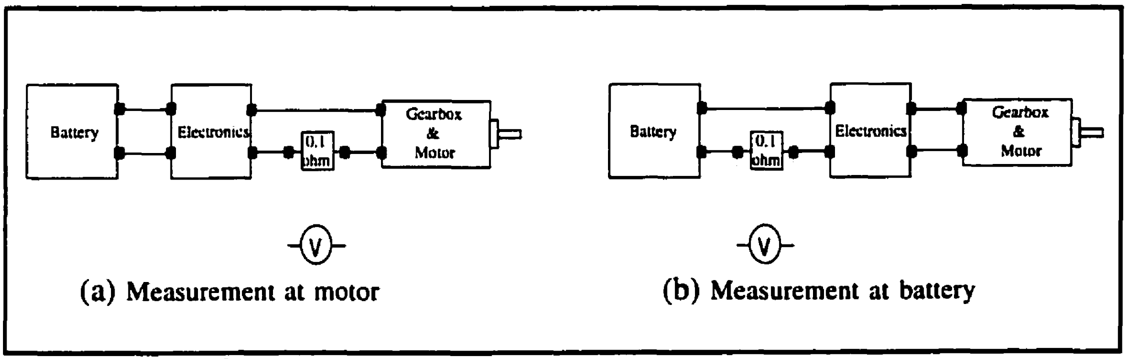
Chapter 6
Bench Testing Results

6.1 Current and Energy Consumption Results

Bench tests to determine the electrical characteristics of the prototype hand have been performed. With the use of an oscilloscope, graphs of motor current vs time were produced and the energy consumption was calculated. Similar current vs time graphs were produced for the VASI 7-11, Otto Bock 7 1/4, and Otto Bock 6 1/2 prosthetic hands. This information was then used to benchmark the prototype hand against conventional prosthetic hands.

6.1.1 Current and Energy Consumption Testing Setup

The motor used by the prototype hand is a MicroMo 1724E, with specifications listed in Appendix F1. Since it was not possible to directly measure current with the oscilloscope, the setup show in Figure 6.1(a) was used. A 0.1 ohm resistor was placed in series with one of the motor leads, and the oscilloscope was used to measure the voltage swings across that resistor, with respect to time. This procedure produced graphs of millivolts vs seconds. Using the relationship V=IR, mV data were transformed into mA. For each setup, three trials were performed and the milliAmp data were averaged.



(a) Measurement at motor

(b) Measurement at battery

Figure 6.1 Measurement Setup

As shown in Figure 6.1, there were two setups used because access to the Otto Bock motors was difficult. Current was measured at the motor as in Figure 6.1(a) for the prototype hand and the VASI 7-11, and measured at the battery as in Figure 6.1(b) for the Otto Bock 7 1/4 and Otto Bock 6 1/2. The reason for doing so was that it would have been difficult to dismantle the Otto Bock hands in order to solder in a 1 ohm resistor directly behind the motor. Instead, the resistor was soldered in at the battery end. There were two potential problems that could occur when measuring the current at the battery end. One was a more noisy signal, and the other was current consumption by the electronics and wires. Both these problems could interfere with the data obtained. To estimate how much this configuration would affect the measurement of current for the Otto Bock hands, the current for the VASI 7-11 hand was measured at both the motor (Figure 6.1(a) setup) and at the battery (Figure 6.1(b) setup). It was observed that there was not a significant difference in the graphs of current vs time. (Refer to Graphs E15, E16, E19 and E20 in Appendix E). The signal was more noisy, but the curves had generally the same shape, peak levels and average levels. The energy consumption for Graphs E15 and E16, which were measured at the motor, was approximately the same as Graphs E19 and E20, which were measured at the battery. It was assumed that the energy consumption for the measurements at the battery end would have been higher, due to the electronics and extra wire length, but this was not the case. The Otto Bock hands use different electronics than the VASI 7-11 hand, however, it was assumed they would produce similar measurements at the battery, as at the motor.

6.1.2 Current and Energy Consumption Data Collection

The data were collected using a Fluke PM3380A Autoranging Combiscope oscilloscope. The data was collected on the screen in the form of a picture showing how the voltage varied with time. These data were then downloaded to a computer and processed using an Excel worksheet. Appendix F2 lists the procedure of downloading the data to computer and transforming the data in such a way as to make it usable to the Excel spreadsheet software.

Three trials were performed for each setup, and the collected data were averaged. This was done for three reasons. Firstly, for any single trial, the current vs time graph had larger random swings in the voltage and therefore, a more 'noisy' signal. By averaging three graphs together, the random 'noise' was reduced and underlying trends in the curve could be more easily observed. Secondly, averaged data provide a better representation of the motor's current behaviour, than a single trial. Thirdly, the graphs were used not only for current and energy consumption observations, but also to time the hands. The graphs reveal how long it took the prosthetic hands to move through a particular mode and averaged graphs produced more reliable timing results.

There were some drawbacks, however, with using averaged graphs. The nature of the data is such that a particular voltage value is associated with a particular instant in time.

If the three sets of data that were being averaged were not in 'phase' with each other, i.e. the start peaks or stop peaks did not line up in time, minor problems could result in the averaged graphs. Since three curves were being averaged, one problem is that a peak current value may be diminished by one third from its actual value, if one of the three curves is completely out of phase. Simply shifting a curve to the right or left would not necessarily correct the problem, as some curves may start at the same time, but take longer to peak. There was no easy way to correct this problem. One method to diminish these errors would be to perform a greater number of trials (trials>20). However, this would require much more time and for the purposes of this analysis was not necessary. Only a handful of the current vs time graphs, experienced the data 'spreading' problem and they have been clearly marked with a large asterisk right on the graph, near the problem area. The other curves are a very good average representation. Since the peak current value information was easily lost in the averaged graphs, the peak current values presented in Tables 6.1 through 6.4 were taken directly from the individual data trials.

The 'spreading' problem described above had no effect on the energy consumption calculations, which are simply additive. To compute the energy consumed by a particular setup, the area under the averaged current vs time graph was calculated. A Riemann sum(27) was used for an area calculation, which is simply a sum of all the averaged milliAmp data, multiplied by the time interval between samples. To verify that this approximate formula was acceptable, a more complicated, self-derived formula was used to compute the actual area under the curve and it was found that the actual area differed by less than one percent of the Riemann sum. Therefore, the Riemann sum formula was used for all area calculations under the graphs. The area computed under the graphs has units of milliAmp hours. The area value is useful because it produces a rough estimate of how many cycles of open-close can be expected from the prototype, for a given sized battery.

6.1.3 Current and Energy Consumption Graph Analysis

Due to the multiple degrees of freedom of the prototype hand, many different grasp configurations are possible. For the purposes of electrical testing, four distinct modes of operation were chosen for the prototype hand. The four modes are: (a) closing/opening empty, (b) closing/opening onto a 51 mm diameter acrylic cylinder, (c) closing/opening onto a 83 mm diameter polyethylene cylinder, and (d) closing/opening with the thumb in the 'Key' grip position onto a credit card. Mode (a) was chosen to approximate the grasp of very small objects and demonstrates maximum opening and closing times. Mode (b) was chosen to approximate the grasp of medium sized objects. Mode (c) was chosen to approximate the grasp of very large objects and also demonstrates minimum opening and closing times. Finally, mode (d) demonstrates the new feature of the prototype hand.

For mode (a), three different cases of closing/opening trials were done. The first case was a pinch with the thumb in opposition to the middle finger, with no glove used. This is shown in Graph E1 for closing, and Graph E2 for opening. Graph E1 shows a very typical data curve, observed in all the 'closing' graphs of the prototype hand. It closely reflects the internal operation of the prototype. This graph will be examined in some detail so that the other graphs can be better understood.

The various regions on Graph E1 have been marked and a dashed average current line has been drawn. On the left side of the graph, in region (I), an initial or starting peak of current is observed. For the prototype motor, this peak is between 600 mA and 800 mA, and has a base time of approximately 200 milliseconds. Region (II) is next, which has an approximately constant current consumption. In this region, the hand is closing but is not compressing any of the *Compression Springs*. The motor only needs to overcome the friction in the hand's mechanisms with a current value of approximately 70 mA. Region (III) begins once the hand's mechanisms begin compressing the *Compression Springs*. Here an approximately linear ramp upward can be observed, starting at 70 mA and ending at 550 mA. In this region, for any given small time interval, the *Compression Springs* compress slightly, thereby increasing the force required (to close the hand further), thereby increasing the motor current needed. The end of region (III) occurs when one of the *Cylinder Spring* mechanisms, described in Section 4.3, reaches its maximum extension(Mode C). When this occurs, all of the remaining force in the *Force Plate* is transferred through the *Cylinder Springs* in Mode C, to form a firm pinch. This represents region (IV). As the pinch develops, the current required to increase the pinch force climbs upwards very quickly. Once the current reaches a predetermined value of approximately 1100 mA, a device known as the energy saver (described in the next paragraph) shuts off all current to the motor. In region (IV) the current peaks at approximately 1200 mA and then suddenly drops down to zero mA. Next, region (V) is the zero region during which no motor current is present.

The energy saver circuit used by the prototype influences the graphs of current vs time and the final pinch force developed by the hand. Referring to region (IV) in Graph E1, high current is running through the motor to generate the torque needed to create the pinch force, while the motor speed is very low, if not zero. This condition causes a high energy drain on the battery, so a device known as the 'energy saver' has been made to shut off the motor current at a predetermined value. The energy saver used by the prototype hand has a shutoff current of approximately 1100 mA, and is the same one used for the VASI 7-11 hand.

If the prototype was operated without the energy saver installed, the current could reach as high as 1600 mA during a pinch. This current level would cause the motor to approach its stall torque and hence a higher pinch force could be obtained. However, without the energy saver in place, if the switch operating the motor current remains activated, the high current will not drop down to zero, but will stay at 1600 mA. In this state, the battery will quickly drain and the motor windings could overheat and be damaged. For this reason, the energy saver is necessary. However, an energy saver modified specifically for the prototype motor is recommended so that higher shutoff currents can be achieved. This will allow for higher pinch forces. It would make the hand consume slightly more energy, but this would be a small amount. The energy use would only increase in region (IV) of Graph E1, but would not affect the energy consumption in the other graph regions. Since the energy use in region (IV) would only be increased, it is estimated that the total energy increase would be about 5 to 10 percent.

There are oscillations in regions (II) and (III) of Graph E1. These are not random fluctuations, but are due to a slightly unaligned mechanism. The motor works a little harder for 180° of a turn and not as hard for the remaining 180°. This was probably a result of inaccurate machining during construction of the prototype hand.

Graph E2 shows the current vs time results for the hand during opening, under the same conditions as Graph E1. The energy required to open the hand is approximately one quarter of the energy required to close the hand, as there are no springs to compress as the hand opens. This energy consumption pattern is quite different from a pair of close/open VASI or Otto Bock graphs. The close/open Graphs E15 to E20, of the VASI 7-11 hand are very similar to each other in shape and in energy consumption. The same is true for the Otto Bock hand Graphs E21 to E28.

The estimated value for energy consumed by a particular setup is recorded in the bottom right hand corner of the current vs time graphs. This value was obtained by calculating the area under the graph and is given in units of mAh. For Graph E1, this value is 0.3045 mAh. For Graph E2, the opening condition for the same setup, the value is 0.1307 mAh. Therefore, for one complete close/open cycle of the prototype hand, with no glove on, where the thumb and middle finger meet, with no object in the hand, the total energy used is: (0.3045+0.1307)= 0.4352 mAh. Assuming the use of a conventional 300 mAh Otto Bock battery for the hand and assuming that all 300 mAh's are available for use, the prototype hand could be expected to perform (300 / 0.4352 = 689.4) approximately 690 cycles, under the conditions given above, until the battery is drained. These results are summarised at the bottom of Tables 6.1 through 6.4.

6.1.4 Current and Energy Consumption Table Summaries

Table 6.1 summarises the results for mode (a) as described in Section 6.1.3 and Table 6.2 shows the results for modes (b) and (c). The first feature in the tables is the closing and opening time for the prototype hand. Closing time is defined as the time it takes the hand to flex from the fully open position to the closed position with a full pinch force developed. For the prototype hand, this is 4 to 5 seconds, depending upon the configuration of the thumb with respect to the fingers. This is far too long and must be improved upon. The issue of time vs pinch force is a problem in itself and is discussed in Section 7.2.1. The other prosthetic hands that were tested close or open in approximately 1 to 1.5 seconds. Tables 6.3 and 6.4 show the close and open times for the VASI 7-11 and Otto Bock hands, respectively. Therefore, the prototype hand is 2 to 4 times too slow compared to these hands.

The 'Closing Current, Average' in the tables, was computed by summing all of the current values for a particular graph and dividing by the amount of time to close. The 'typical, region (II)' current for the prototype hand, or the 'typical, flat region' current for the VASI 7-11 hand, was the constant current observed during operation. This is represented by the flat regions in the associated graphs. By drawing a flat line through these regions, the typical currents are estimated. As noted in Section 6.1.2, some of the averaged graphs have phase problems which diminish the peak values. Therefore, all 'peak*' values in Tables 6.1 through 6.4 have been taken from the highest peak of the single trial raw data. Due to the great volume of single trial data, only the averaged Graphs E1 to E28 are presented.

The 'Opening Current, Average' values and 'peak*' values are computed in the same manner as described for the 'Closing Current' values. The 'Energy Consumption' values located in the bottom right hand corner of the graphs are summarised in the tables. An estimated value for the number of close/open cycles for a particular hand task is also provided, based on the use of a standard 300 mAh Otto Bock battery.

Prototype Hand	No Glove, Pinch between Thumb and Middle finger.	No Glove, Thumb slips between Index and Middle finger during pinch.	With Glove, Pinch between Thumb and Middle and Index finger
Graph for Close: Graph for Open:	E1 E2	E3 E4	E7 E8
Close Time: Open Time:	4.0 seconds 3.5 seconds	4.8 seconds 3.8 seconds	4.3 seconds 3.5 seconds
Closing Current, Average: typical, region (II): min/max, region (III): peak,* region (IV):	 274 mA 70 mA 70 mA / 550 mA 1245 mA	 335 mA 70 mA 70 mA / 650 mA 1265 mA	 310 mA 70 mA 70 mA / 500 mA 1335 mA
Opening Current, Average: peak:*	 134 mA 1225 mA	 119 mA 1280 mA	 130 mA 1370 mA
Energy Consumption, Closing: Opening: Total:	 0.3045 mAh 0.1307 mAh 0.4352 mAh	 0.4419 mAh 0.1235 mAh 0.5654 mAh	 0.3701 mAh 0.1263 mAh 0.4964 mAh
Estimated # of cycles on 300 mAh battery:	690 cycles	530 cycles	600 cycles

* Peak values are taken directly from single trial raw data

Table 6.1 Prototype Hand Summary for closing/opening Empty

Prototype Hand	No Glove, 51.1 mm diam cylinder	With Glove, 51.1 mm diam cylinder	With Glove, 83 mm diam cylinder	With Glove, credit card, side pinch
Graph for Close: Graph for Open:	E5 E6	E9 E10	E11 E12	E13 E14
Close Time: Open Time:	3.4 seconds 2.7 seconds	3.5 seconds 2.7 seconds	2.9 seconds 2.4 seconds	4.7 seconds 3.6 seconds
Closing Current, Average: typical, region (II): min/max, region (III): peak,* region (IV):	 327 mA 70 mA 70 mA / 550 mA 1265 mA	 362 mA - 70 mA / 550 mA 1235 mA	 389 mA - 100 mA / 550 mA 1295 mA	 380 mA 70 mA 70 mA / 550 mA 1275 mA
Opening Current, Average: peak:*	 138 mA 1205 mA	 146 mA 1310 mA	 170 mA 1430 mA	 138 mA 1330 mA
Energy Consumption, Closing: Opening: Total:	 0.3090 mAh 0.1037 mAh 0.4127 mAh	 0.3522 mAh 0.1093 mAh 0.4615 mAh	 0.3135 mAh 0.1132 mAh 0.4267 mAh	 0.4962 mAh 0.1379 mAh 0.6341 mAh
Estimated # of cycles on 300 mAh battery:	725 cycles	650 cycles	700 cycles	473 cycles

* Peak values are taken directly from single trial raw data

Table 6.2 Prototype Hand Summary for closing/opening with Objects

VASI 7-11	No Glove, Empty (measured at motor)	No Glove, 51.1 mm diam cylinder (measured at motor)	No Glove, Empty (measured at battery)
Graph for Close:	E15	E17	E19
Graph for Open:	E16	E18	E20
Close Time:	0.83 seconds	0.33 seconds	0.83 seconds
Open Time:	0.87 seconds	0.35 seconds	0.87 seconds
Closing Current,			
Average:	279 mA	458 mA	264 mA
typical, flat region:	160 mA	180 mA	155 mA
peak:*	1485 mA	1315 mA	1360 mA
Opening Current,			
Average:	306 mA	485 mA	293 mA
typical, flat region:	170 mA	190 mA	190 mA
peak:*	1480 mA	1530 mA	1520 mA
Energy Consumption,			
Closing:	0.0643 mAh	0.0420 mAh	0.0609 mAh
Opening:	0.0739 mAh	0.0472 mAh	0.0709 mAh
Total:	0.1382 mAh	0.0892 mAh	0.1318 mAh
Estimated # of cycles on 300 mAh battery:	2170 cycles	3360 cycles	2275 cycles

* Peak values are taken directly from single trial raw data

Table 6.3 VASI 7-11 Summary of Current Measurements

Otto Bock 7 $^1/_4$ Otto Bock 6 $^1/_2$	Otto Bock 7 $^1/_4$ With Glove, Empty	Otto Bock 7 $^1/_4$ With Glove, 51.1 mm diam cylinder	Otto Bock 6 $^1/_2$ With Glove, Empty	Otto Bock 6 $^1/_2$ With Glove, 51.1 mm diam cylinder
Graph for Close:	E21	E23	E25	E27
Graph for Open:	E22	E24	E26	E28
Close Time:	1.55 seconds	1.6 seconds	1.43 seconds	1.0 seconds
Open Time:	1.58 seconds	1.4 seconds	0.90 seconds	0.42 seconds
Closing Current,				
Average:	406 mA	441 mA	251 mA	251 mA
peak:*	945 mA	925 mA	635 mA	615 mA
Opening Current,				
Average:	470 mA	480 mA	260 mA	226 mA
peak:*	965 mA	1025 mA	635 mA	615 mA
Energy Consumption,				
Closing:	0.1747 mAh	0.1958 mAh	0.0998 mAh	0.0698 mAh
Opening:	0.2064 mAh	0.1866 mAh	0.0649 mAh	0.0264 mAh
Total:	0.3811 mAh	0.3824 mAh	0.1647 mAh	0.0962 mAh
Estimated # of cycles on 300 mAh battery:	787 cycles	785 cycles	1822 cycles	3120 cycles

* Peak values are taken directly from single trial raw data

Table 6.4 Otto Bock 7$^1/_4$ & 6$^1/_2$ Summary of Current Measurements

6.1.5 Current and Energy Consumption Table Analysis

6.1.5.1 Effects of the Glove

A glove normally used for the VASI 7-11 hand, was heated and stretched over the prototype hand, to determine the effect of the glove on the prototype hand. A glove is necessary since it makes the prototype hand look more cosmetic and protects it somewhat from the elements. Normally, a conventional VASI 7-11 glove would not be suitable for use with the prototype hand, since it does not fit well and is prone to tearing near the thumb and at the base of the pinky finger. Nevertheless, the effect on energy consumption and timing when using a glove on the hand is important to anticipate. It may be possible to use a modified version of the VASI 7-11 glove, with the prototype. Such a modified glove may decrease the prototype hand performance by only 10 percent.

Referring to Table 6.1, the information within first and third columns can be compared. The data were collected under two nearly identical setups, except that one set of trials was done with the glove on and other set had no glove. The close/open times reveal that when the glove is on the hand, it takes 0.3 seconds longer to close, which is an increase in time of 9 percent. It takes the same time to open the hand with or without a glove. The probable reason for this result is that when the glove is in its 'rest' state, the glove's shape corresponds to the hand in the open position. When the hand is closed, it must fight against the 'rest' state of the glove, to stretch it into the closed position. In essence, the glove acts like a spring. When the hand is opened, there is no resistance from the glove since it is trying to return to its 'rest' state, therefore the only factor limiting the opening time is the motor speed.

Referring back to the first and third columns of Table 6.1, note that the average current to close the hand is 13 percent higher with a glove. The average current to open the hand is approximately the same. These results follow the argument that the hand must work harder to close with the glove on, but does not need to work as hard to open. The first and second columns of Table 6.2 present somewhat similar results. The average current to close is 11 percent higher with a glove, however, here the average open current is also 6 percent higher with the glove.

When the hand uses the glove more energy is consumed. In Table 6.1 the comparison of 'Total' energy used in the first and third columns shows that the hand uses 14 percent more energy with the glove on. To break this result down further, the energy used to close the hand is 22 percent higher with a glove, but the energy is approximately the same to open the hand. In Table 6.2 similar results in the first and second columns can be observed. The 'Total' energy used by the hand is 12 percent higher with the glove. It takes 14 percent more energy to close the hand with a glove and takes 5 percent more energy to open the hand with the glove.

These results reveal that there is a slight negative effect on performance of the hand when using a VASI 7-11 glove. Compared to the benefits such as cosmesis and protection from the elements, these reductions in performance, of about 10 to 15 percent are considered acceptable. With some modifications to an ordinary VASI 7-11 glove, it could be possible to greatly reduce the tearing problems. This possibility was discussed with staff in the Myoelectrics Service at Bloorview MacMillan Centre. There was a discussion regarding the use of flexible PVC patches that could be glued onto the outer thumb area and the pinky finger area. However, the ideal case would be to have a custom-made glove, particularly for this type of hand with flexible fingers and a swivelling thumb. Such a custom glove would preferably have small 'corrugations' in the knuckles of the fingers and thumb and a 'corrugated' area around the swivelling thumb. Such a glove could be made so that it would have no negative impact on the hand performance.

6.1.5.2 Effects of Different Configurations

Depending on the size of the object or the position of the thumb, the prototype hand will consume different amounts of energy. Generally, the smaller the object, the more energy the hand consumes during a grasp. This is because it must close and open for a longer period of time. Referring back to the tables, a comparison of three columns that use the glove with progressively larger objects can be analysed. The third column of Table 6.1 and the second and third columns of Table 6.2, show a hand with no object, with a 51 mm cylinder and an 83 mm cylinder, respectively. These columns show a steady decrease in time to close, time to open and total energy used.

With the thumb to the side the hand will perform a 'key' grip. In this grasp pattern, the hand consumes the most amount of energy because all the fingers can fully close and therefore all the *Compression Springs* are almost fully compressed. Comparing the case of the hand in a tri-digital pinch, shown in the third column of Table 6.1 to the case of the 'key' grip shown in the fourth column of Table 6.2, there is an increase in the time to close, the time to open and the energy used. The increase in energy is approximately 28 percent. This extra energy expenditure is an integral part of the design when using the thumb in the 'key' grip position and there is no easy way to reduce this energy loss without major redesign.

6.1.5.3 Prototype Hand Compared to VASI 7-11

The prototype hand is slower and uses more energy than the VASI 7-11 hand. The first columns of Table 6.1 and Table 6.3, show the differences in closing and opening times. The time for each hand to go from the open position, to a closed position with a full pinch force is considered. The prototype takes 4.0 seconds to achieve this, while the VASI 7-11 hand takes 0.83 seconds. This shows the prototype hand to be almost five times slower than the VASI 7-11 hand. However, if the time from the open position to a closed position where the fingers just touch the thumb is considered, the prototype hand takes approximately 1.5 seconds to achieve this. It then takes a further 2.5 seconds to develop the maximum pinch force, while the *Compression Springs* compress. In this sense, from a cosmetic point of view, the prototype takes approximately 2 times as long as the VASI 7-11 hand to 'close', with fingers just touching. When the prototype hand is opening, it has a similar timing disadvantage. For the first 1.5 seconds during opening the *Compression Springs* are being uncompressed, with no visible motion at the fingers or thumb. The reason for this 'opening lag' is due to the operation of the *Cylinder Spring* mechanism as explained in Section 4.4. After the *Compression Springs* become uncompressed, the hand takes a further 1.5 seconds to open, during which finger motion is visible, followed by 0.5 seconds of 'semi-opening' until the mechanism cannot move and the energy saver shuts off the current to the motor.

The 'Average' current during closing for both hands is about the same. However, the 'typical' current during closing, reveals more about the internal workings of the hands. The 'typical' current along with motor specifications, can be used to estimate how difficult it is to close each hand. The 'typical, region (II)' current for the prototype hand is approximately 70 mA. This is the current level from the time the hand is open, to the time the fingers just touch the thumb. The corresponding 'typical, flat region' current for the VASI 7-11 hand is 160 mA. The prototype hand uses a 6 volt motor with a torque constant of 1.00 oz-in/Amp. The VASI 7-11 hand uses a 4.5 volt motor with a torque constant of 0.603 oz-in/Amp. Because VASI 7-11 hand is being over driven with a 6 volt battery, it probably has an actual torque constant of about (0.603 oz-in/Amp)*(6 volt / 4.5 volt) = 0.80 oz-in/Amp. Using these torque constants and the 'typical' currents during close for both hands, the motor torque to close these hands can be compared. It takes approximately 0.07 oz-in of motor torque for non-adaptive closure of the prototype hand and 0.13 oz-in of motor torque to close the VASI 7-11 hand. The prototype hand motor uses a 22:1 gearbox operating at 73 percent efficiency, while the VASI 7-11 motor uses a 8.3:1 gearbox operating at 81 percent efficiency. Therefore, it takes 1.12 oz-in of torque to overcome friction in the mechanism of the prototype hand during non-adaptive closure. Similarly, it takes 0.87 oz-in of torque to overcome friction to close the VASI 7-11 hand. However, these results are still biased because the prototype hand takes approximately twice as long to close (during non-adaptive close, region (II), Graph E1) as the VASI 7-11 hand. To double the closing speed, the current would have to be doubled to produce double the closing torque by prototype motor. To close the prototype hand within the same amount of time as the VASI 7-11 hand, the prototype would need 2.24 oz-in of torque supplied. The VASI 7-11 hand only needs 0.87 oz-in of torque supplied. This shows that the prototype has 2.6 times more internal resistance to closing (during non-adaptive close, region (II), Graph E1) than a VASI 7-11 hand.

The 'Opening Current, Average' of the prototype hand is 138 mA, while for the VASI 7-11 the 'Opening Current, Average' is 306 mA. The 'typical' opening current in this region for the prototype hand can be read from Graph E2 and is between 90 mA to 50 mA, depending on the state of opening. The VASI 7-11 hand has a 'typical, flat region' opening current of 170 mA, which is comparable to its 'typical, flat region' closing current. By performing a similar analysis to the one in the preceding paragraph, similar results are obtained. The prototype hand is 1.8 times more resistant to opening (region (III), Graph E2) than the VASI 7-11 hand.

The energy consumed by the prototype hand is approximately 3.2 to 4.6 times more than the VASI 7-11 hand. This result translates directly to battery life. If the prototype hand makes use of the same battery used by the VASI 7-11 hand, the prototype hand would wear out the battery 3.2 to 4.6 times faster.

In summary, compared to the VASI 7-11 hand, the prototype hand:

- takes 5 times longer to achieve a full pinch.
- takes 2 times longer to reach a tri-digital pinch position.
- has the approximately the same average closing motor current.
- has 54 percent less average opening motor current.
- has 2.6 times more mechanism resistance during an empty close.
(non-adaptive region (II), Graph E1)
- has 1.8 times more mechanism resistance during opening.

(non-compressed region (III), Graph E2)

- consumes 320 to 460 percent more energy, depending on the task.

6.1.5.4 Prototype Hand Compared to Otto Bock 6 1/2

The prototype hand is slower and uses more energy than the Otto Bock 6 1/2 hand. Comparing the third column of Table 6.1 with the third column of Table 6.4, the prototype hand is observed to take 3 times longer to close and almost 4 times longer to open, than the Otto Bock 6 1/2 hand. It must be noted that the Otto Bock 6 1/2 hand has a very different configuration from that of the VASI 7-11 hand. The Otto Bock 6 1/2 uses two motors within the hand, one for a fast close and the other for a slow close with higher torque. The Otto Bock hand actually takes 0.6 seconds to close to a position where the thumb and fingers meet and an additional 0.8 seconds to form a full pinch. The prototype hand takes 1.5 seconds to close to a position where the thumb and fingers meet and an additional 2.5 seconds to form full pinch. This means the prototype hand takes 2.5 times longer to close to a tri-digital pinch position, with no force developed.

The 'Closing Current, Average' of the Otto Bock hand with the glove on is 251 mA, while the 'Closing Current, Average' for the prototype hand using a glove is 310 mA. The Otto Bock 6 1/2 hand operates with a four cell battery, at 4.8 volts, while the prototype hand operates with a standard five cell, 6 volt battery. Therefore, the Otto Bock 6 1/2 hand would probably consume less current to achieve the same amount of motor torque, if it also used a 6 volt system. The inner efficiencies of the Otto Bock 6 1/2 hand and the prototype could not be compared, because the motor characteristics for the Otto Bock 6 1/2 were not available for this analysis.

The 'Opening Current, Average' for the prototype hand is 130 mA, and 260 mA for the Otto Bock 6 1/2 hand. Even if the Otto Bock 6 1/2 hand used a 6 volt system, the prototype hand would still use less average current. Again, because the motor specifications for the Otto Bock 6 1/2 hand are not known, it is difficult to make further comparisons based on the current differences alone.

The energy consumed by the prototype is 3.0 to 4.8 times more than the Otto Bock 6 1/2 depending upon the task. Some technical specifications about the Otto Bock system 2000 hands are listed in Appendix F3.

In summary, compared to the Otto Bock 6 1/2 hand, the prototype hand:

- takes 3 times longer to achieve a full pinch.
- takes 2.5 times longer to reach a tri-digital pinch position.

- uses 24 percent more average motor current during close*
- uses 50 percent less average motor current during opening*

*the operating voltage of the Otto Bock 6 1/2 is 4.8 volts, compared to 6 volts for the prototype. Also, the Otto Bock 6 1/2 uses a dual motor system.

- consumes 300 to 480 percent more power, depending on the task.

6.1.5.5 Prototype Hand Compared to Otto Bock 7 1/4

The Otto Bock 7 1/4 hand was designed for teenagers or for women. As such, it is aimed at a different target age than that of the prototype hand, which is aimed towards the 7-to-11 year age group. The prototype hand is currently too large in some dimensions such as palm length and palm thickness, for its own target age group. Because of its larger size, it could potentially compete with the target market for the Otto Bock 7 1/4 hand, so a comparison with this hand has been performed.

Comparing closing time in the third column of Table 6.1 to the closing time in the first column of Table 6.4, the prototype hand is observed to take 2.8 times longer to form a full pinch, than the Otto Bock 7 1/4 hand. The Otto Bock 7 1/4 hand uses a design which employs an automatic transmission to achieve a fast close, followed by a high torque for pinch. In this way, the Otto Bock 7 1/4 hand takes approximately 0.8 seconds to close to a position where the thumb and fingers meet and an additional 0.7 seconds to form a full pinch. The prototype hand takes 1.5 seconds to close to a position where the thumb and fingers meet and an additional 2.5 seconds to form a full pinch. This means the prototype hand takes 1.9 times longer to close than the Otto Bock 7 1/4 hand, for the case where both hands start from their open positions and end with fingers just touching the thumb.

The 'Closing Current, Average' used by the prototype hand is 310 mA compared to 406 mA for the Otto Bock 7 1/4 hand. Both hands use a 6 volt system and use the same battery. The Otto Bock 7 1/4 hand motor and transmission have not been fully investigated and as such, no comparisons can be made regarding relative hand internal efficiencies. The 'Opening Current, Average' for the prototype hand is 130 mA, compared to 470 mA for the Otto Bock 7 1/4 hand.

A surprising result was the large amount of energy used by the Otto Bock 7 1/4 hand. The prototype hand uses only 20 to 30 percent more energy than the Otto Bock 7 1/4 hand, depending on the task. This is a substantially lower difference than the 300 to 480 percent differences with the other prosthetic hands tested. As explained in Section 7.2.1, the use of this type of automatic transmission can provide a great pinch force vs speed benefit.

In summary, compared to the Otto Bock 7 1/4 hand, the prototype hand:

- takes 2.8 times longer to achieve a full pinch.
- takes 1.9 times longer to reach a tri-digital pinch position.
- uses 24 percent less average motor current during close
- uses 73 percent less average motor current during opening
- consumes 20 to 30 percent more power, depending on the task.

6.1.6 Current and Energy Consumption Results Summary

The prototype hand is slower in opening and closing, and uses more power than any of the other prosthetic hands it has been compared to. It has a comparable 'Closing Current, Average' to the VASI 7-11, a slightly higher 'Closing Current, Average' than the Otto Bock 6 1/2 and a much lower 'Closing Current, Average' than the Otto Bock 7 1/4 hand. The prototype hand has a much lower 'Opening Current, Average' than any of the other hands. These average current results may seem promising at first glance, but the fact that the prototype hand takes 3 to 4 times longer to close or open than any other hand must also be considered. If the gearbox on the prototype hand was changed to make it close or open twice as fast, the motor would need twice the current levels listed, to generate the same torque required. This is because friction in the hand's mechanisms would remain the same. Therefore, in order to make the prototype hand close as fast as the other prosthetic hands, the prototype hand would incur the penalty of higher average currents than the other prosthetic hands.

The prototype hand consumes 3 to 5 times more energy than the VASI 7-11 or the Otto Bock 6 1/2 hands, both of which are aimed at the same target age group. This means that if all these hands were to use the same battery, the prototype hand would drain the energy 3 to 5 times faster. Unfortunately, this large energy consumption is inherent in the *Cylinder Spring* mechanism design.

By using Graphs E1 through E28 and the summary Tables 6.1 to 6.4, many other comparisons and extrapolations can be made with regards to the prototype hand vs the other prosthetic hands. The information has been presented in such a way as to allow broad uses for other types of comparisons.

6.2 Pinch Force Results

The pinch force produced by a conventional prosthetic hand has a great influence on the usefulness of the hand in grasping objects. Generally, the higher the pinch force, the better a conventional prosthetic hand is able to securely grasp an object. This is because a high pinch force results in greater static friction between that object and the hand. The importance of pinch force is the same for the prototype hand in some respects, and yet is not as important in other respects. The prototype hand was built with four very different features not currently available with conventional prosthetics. They are, independent adaptive finger closure, 'flexing' fingers, compliant silicone under the fingers (under the glove) and a movable thumb. The main purpose of all these design additions was for the improvement of object grasp and stability. Therefore, the importance of pinch force is reduced by these design features for certain grasping patterns. For other grasping tasks, however, such as grasping a knife or fork, high pinch force is still very important.

The prototype hand was designed to theoretically produce 6 lbf to 8 lbf of pinch, but has fallen short of this goal. Testing has shown that the prototype can achieve a maximum pinch force of 3.2 lbf in a tri-digital pinch grasp pattern. The reason for this lower pinch force, was unexpected energy loss during the operation of the *Cylinder Spring* mechanism which provides the adaptive grasp.

6.2.1 Pinch Force Testing Setup

Due to the type of meter used for pinch force testing, only three types of tests were applicable for the prototype hand. They were the tri-digital pinch, an index finger to thumb pinch and the 'key' grip pinch (with the thumb in the side position). These pinch tests were performed with the VASI 7-11 glove on and also with no glove. In addition, three other prosthetic devices were tested with the same meter. They were the VASI 7-11 hand, the Otto Bock 6 1/2 and the Otto Bock 7 1/4 hand. The only type of pinch test possible with these conventional prosthetics was the tri-digital pinch. There are also some results presented for other types of hands taken from literature. Also included is the Author's pinch force and the average pinch force for men. These values were included to create a reference point to the other values indicated. The two literature sources listed in this table are the Montreal hand(7) and the Paul Hu experimental hand(23). These prostheses are both experimental hands which posses similar features to the prototype hand and are therefore important benchmarks. Both these hands are capable of the index finger to thumb pinch and the 'key' grip pinch, but unfortunately these data were not available. All pinch force values are summarised in Table 6.5.

	Tri- digital Pinch	Index Finger to Thumb Pinch	'Key' grip Pinch
Prototype Hand:	2.8 - 3.2 lbf	2.6 - 2.8 lbf	1.4 - 1.9 lbf
Prototype Hand, with Glove:	2.8 - 2.9 lbf	2.4 - 2.6 lbf	1.2 - 1.4 lbf
VASI 7-11 Hand:	7.2 - 8 lbf	-	-
Otto Bock 6 1/2:	7 - 9 lbf	-	-
Otto Bock 7 1/4:	27 lbf	-	-
Montreal Hand(7):	10.1 lbf	-	-
Paul Hu(23), Experimental Hand:	3.0 lbf	-	-
Author:	18 lbf	12 lbf	12 lbf
Average male:	13 - 16 lbf	-	-

Table 6.5 Pinch Force Results

6.2.2 Pinch Force Analysis

The results in Table 6.5 show that the maximum pinch force of the prototype is 3.2 lbf, which is approximately 60 percent less than the theoretically predicted 8 lbf, as discussed in Section 4.2.

It was suspected that the prototype mechanism had higher than expected friction, but this was not the case. It was very difficult to predict frictional effects when designing a device as complicated as the prototype, however, a prediction was made. It was assumed originally when the motor for this hand was selected, that approximately 22.5 lbf (100 N) of pulling force at the *Ball Nut* would be lost due to mechanism friction, as shown in the motor selection calculations in Appendix D. This frictional loss would impact the final achievable pinch force because the force would no longer be available to be transferred to the finger tips. The electrical current analysis of Section 6.1.5.3 compared the prototype hand to the VASI 7-11 hand. It was determined that the prototype hand needed approximately 1.12 oz-in of torque to overcome the friction within its mechanisms during non-adaptive closing. When this value for the required motor torque is transferred through the *Lead Screw* to the *Ball Nut*, it translates into a force of 10.1 lbf (45 N). Therefore only 10.1 lbf of frictional force was present within the hand during non-adaptive closing. This is less than half the predicted hand friction. Therefore, it can be concluded that friction within the hand is not responsible for the reduced pinch force because it had been taken into account during the original design. In fact, because there is only 10.1 lbf of frictional force in the prototype during close, there should have been slightly more pinch force than originally predicted.

The *Cylinder Spring* mechanism, which provides the adaptive grasp, is the source of the problem leading to the lower pinch force. It was initially expected that this mechanism would reduce the pinch force of the hand by 10 percent of the theoretical maximum of 8 lbf, to yield a pinch of 7.2 lbf. However, this initial expectation was in error, because it did not account for the combined energy loss of all the adaptive springs during closure, which represents an additional loss of approximately 13.5 lbf (60 N), from the *Force Plate*. Also, it did not consider that the thumb's adaptive spring needed to have a higher force than the original design. This was because it had to overcome the *Thumb Return Spring* and this added force loss of about 9 lbf (40 N) was also not taken into account.

To better understand how the loss occurred, refer back to Graph E1 in Appendix E, at region (III) on the graph. This region corresponds to the current level in the motor while the hand is closing and adapting the fingers. Initially, on the left side of region (III), there is almost no compression of the *Compression Springs* within the *Cylinder Spring* mechanism. As time progresses, a steady climb in the current level is observed as the *Compression Springs* become more and more compressed. The right side of region (III) corresponds to the prototype hand having achieved a full adaptive grasp pinch. The next stage in the graph is region (IV) where there is a sharp climb in current as the hand forms the maximum pinch force. The important feature in this graph, was the current level that region (III) ended at. In this case, that level was approximately 600 mA. Therefore, the motor (through the gearbox) has had to supply 9.64 oz-in of torque to the *Lead Screw*, just to overcome mechanism and *Compression Spring* resistance, but still has not developed full pinch. According to the revised motor calculations in Appendix D1, the motor (through the gearbox) is only capable of producing a maximum of 15.90 oz-in of torque. This leaves only 6.54 oz-in of torque available for developing a pinch. When passed through the *Lead Screw* assembly, this torque will develop only 58.7 lbf (261 N) of pull at the *Force Plate*. The theoretical maximum pinch that can be achieved with 58.7 lbf available at the *Force Plate* (based on a Working Model 2D analysis) is only 4.2 lbf. Original calculations had assumed that approximately 122 lbf (543 N) would have been available at the *Force Plate* to develop a pinch of 8.2 lbf. Also, the theoretical maximum computed on Working Model is based on specific link-to-link geometries. The geometries entered into the model were within 2-3 percent of the geometries subsequently machined into the prototype. However, the model was fairly sensitive to small geometry changes within the fingers, or to alignment between finger and thumb. It is expected that this difference could account for an additional pinch loss of 0.45 to .90 lbf (2 to 4 N), as observed by the many trials performed on Working Model.

6.2.3 Pinch Force Summary

The prototype hand does not produce a pinch force as high as was theoretically expected and is only capable of a maximum of 3.2 lbf in a tri-digital pinch. This is about 60 percent less than was expected. The reason for this result is not due to frictional losses, but due to mainly to unpredicted losses occurring as a result of the *Cylinder Spring* mechanism. The prototype hand currently produces 60 percent less tri-digital pinch force than a VASI 7-11 hand and 65 percent less pinch force than an Otto Bock 6 1/2 hand, both of which are aimed at the same target age group of 7 to 11 years of age. The importance of high pinch force is a reduced priority for the prototype hand due to the fact that it has four added design features aimed at improving object grasp and stability. Nevertheless, high pinch force is required for certain precision tasks, such as using a knife and fork and in this respect, the prototype hand must be made to pinch harder. Therefore, the 3.2 lbf pinch is sufficient to hold and secure a wide variety of objects, but is not sufficient when performing certain precision tasks.

6.3 Pull-Out Test Results

The purpose of the pull-out tests is to attempt to benchmark the prototype hand against similar tests performed on the VASI 5-9 hand by Joiner(26). These tests were performed with a similar setup to that used by Joiner(1994) and correlate very well with the modified silicone finger tip results of Joiner. If the prototype hand was able to match the pinch force of the regular VASI 5-9 hand, the results show that it would be more difficult to 'pull out' objects from the prototype. Further experimentation with the 'pull out' apparatus reveals that the prototype hand can hold grasped objects more securely than a conventional prosthetic hand, even though it has 60 to 65 percent less pinch force.

6.3.1 Pull-Out Test Setup

There were a number of variations from the setup used by Joiner for the pull out tests. Firstly, Joiner had removed the VASI 5-9 hand's motor and replaced it with an apparatus to provide a constant torque during the tests. This torque produced a constant pinch force of 10 lbf upon the various objects tested by the VASI 5-9 hand. The constant torque device used by Joiner was made specifically for the VASI 5-9 hand. It was not feasible to modify the prototype hand for this device, nor to build a similar device to provide this constant force. Instead, the prototype hand relied on its motor to provide the pinch necessary to hold objects. This introduced a problem in that it was never exactly known how hard the hand was pinching an object. It was assumed that the pinch was approximately 2.9 lbf, which is the maximum pinch force of the hand with a glove. To verify this assumption, the force meter was used periodically between tests, to verify that the hand was pinching with 2.9 lbf.

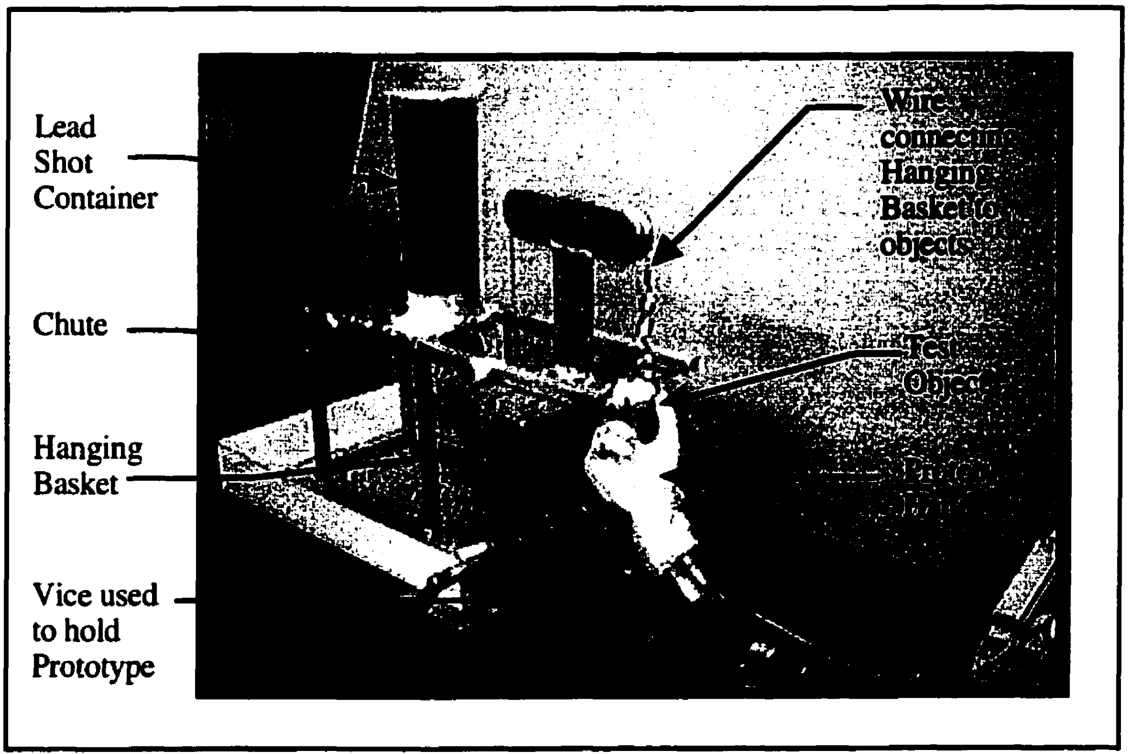


Figure 6.2 Setup of Pull Out Test

Figure 6.2 shows a typical setup of the prototype hand with the apparatus, during a pull out test. The lead shot container can be seen on the left side of the picture. At the base of this container is a chute with a gate. When the gate is opened, lead shot rushes down the chute into the hanging basket. The gate is opened and closed by hand since time was not being recorded in the experiments. The hanging basket is suspended from a wire which is connected to the test object. The wire passes over an apparatus with two pulleys, so that wire can be positioned perpendicular to the ground plane, above the test object and above the hanging basket. As the hanging basket is filled with lead shot, its weight increases. The tension in the wire holding the basket is equal to the weight of the basket. In this way, the 'pull out' force is gradually applied to the test object, which is connected to other end of the wire. The prototype hand is held securely and rigidly in place at a fixed angle, by a vice. The vice is in turn clamped to the table top.

There were seven test objects for the pull out tests and five trials were performed for each object. The tests were randomised so that a total of 35 trials were performed in random order. The purpose of this was to diminish possible sources of error, such as battery life or glove damage. The prototype hand was securely clamped down within the vice at the start of the trials. This was easy to do since the prototype has flat sides on either side of the palm. The back of the palm was at an angle of 39° with the table top. Figure 6.3 shows the hand orientation.

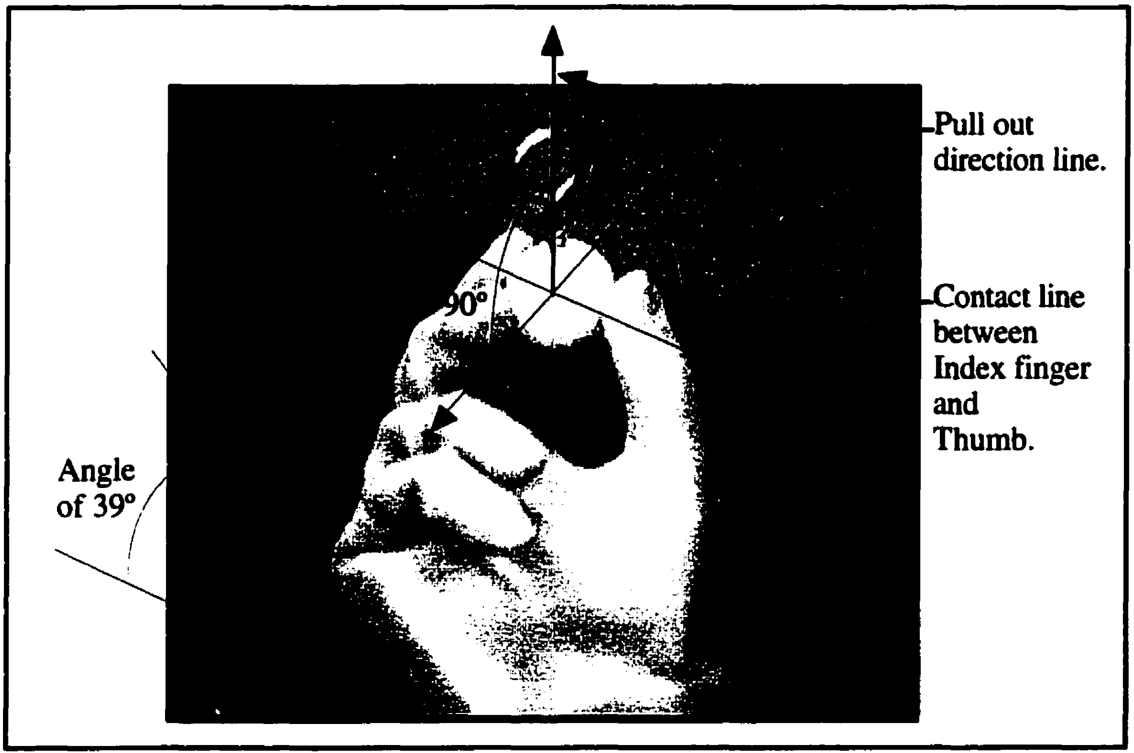


Figure 6.3 Orientation of Prototype Hand during Pull Out Tests

The purpose of orienting the hand in this fashion is to ensure that the 'pull out direction' line shown in Figure 6.3 was perpendicular to the contact line between the index finger and the thumb. In this orientation, the object will slide out from in between the fingers and thumb. The slide out direction will be approximately tangent to the finger and thumb tips. This is the same orientation used for the VASI 5-9 hand in the "0° angle" tests performed by Joiner. Orienting the prototype hand in this way allows for the comparison of the prototype results with the "0° angle" results of Joiner. Appendix G shows the raw data collected by the trials, and also shows a picture (Figures G1 through G7) of the grasp for each object, just before a pull out test was performed.

6.3.2 Pull-Out Test Analysis

Table 6.6 provides a summary of results for the pull out tests. There is a sample mean value and a corresponding sample standard deviation value provided for each object.

	Prototype 2.9 lbf pinch		**'Scaled' Prototype** 10 lbf pinch	**VASI 5-9 standard** (26) 10 lbf pinch		**VASI 5-9 silicone** (26) 10 lbf pinch	
	s. mean (lbf)	s. σ (lbf)	mean (lbf)	s. mean (lbf)	s. σ (lbf)	s. mean (lbf)	s. σ (lbf)
1/2" Delrin sphere	2.59	0.40	8.81*	5.22	0.23	6.45	0.20
1" Delrin sphere	2.85	0.70	9.69*	7.70	0.27	8.79	0.67
7/8" Delrin Flat	4.19	0.54	14.25*	-	-	-	-
1" Delrin Flat	-	-	-	11.71	0.21	14.35	0.42
2" Acrylic Cylinder	6.45	0.63	21.93*	-	-	-	-
2" Delrin Cylinder	-	-	-	10.89	0.17	15.52	0.42
1 1/4" wood sphere	3.39	0.95	11.52*	-	-	-	-
2 3/16" wood sphere	4.68	0.61	15.91*	-	-	-	-
3" wood sphere	5.12	0.37	17.41*	-	-	-	-

* values taken from first column and multiplied by scaling factor of 3.4, to simulate prototype with 10 lbf of pinch.

Table 6.6 Pull Out Test Results for Prototype, and VASI 5-9 hand(26)

The data shown for the VASI 5-9 tests were taken from the raw data in Appendix 3 of the thesis document of Joiner(26). There were no standard deviation values published with his data, so they were recalculated and included along side the mean values of his data.

All of the data taken from Joiner's results are for the "0° angle" configuration specified in his thesis, which corresponds to the orientation used for the prototype hand for its pull out tests.

In the data of Table 6.6, note that the prototype hand is only pinching with about 2.9 lbf, compared to the 10 lbf of pinch exerted upon objects with the VASI 5-9 hand. To allow for a better comparison between the prototype and the VASI 5-9 hand, it has been assumed that the 'pull out' force results of the prototype hand in the first column are scalable. In other words, if the prototype hand were able to pinch with 10 lbf ,which is 3.4 times more than its actual pinch, then it would be expected that the 'pull out' force results would be 3.4 times more as well. The rational behind this assumption is that the frictional force between the fingers and the object is proportional to the pinch force. The frictional force is equal to the force normal to the object surface (pinch force), multiplied by the friction coefficient. Therefore, if the pinch force is 3.4 times higher, the friction should be 3.4 times higher. If the friction is 3.4 times higher, then it would be assumed that the pull out force required to remove an object from the hand would be 3.4 times higher as well. Of course, this assumes a linear relationship between frictional force and pull out force.

There has been a column included in Table 6.6 labelled as 'Scaled' Prototype. The values in this column are the mean force values from the first column multiplied by a scaling factor of 3.4. Unfortunately, there are no experimental results within the data to confirm this assumption. In order to experimentally confirm this assumption, the cutoff current of the energy saver circuit could be reduced to some lower value. This would then make the prototype hand pinch with a consistently lower pinch force. The experiment could then be run again with the same setup. The results of the new and old experiments could then be compared to see what effect the lower pinch force had on pull-out results.

There are seven objects presented in Table 6.6, four of which have been tested by both the prototype hand and the VASI 5-9 hand. The first of these is a 1/2" sphere, shown in Figure G1 of Appendix G. As shown in Table 6.6, the force required to pull out the 1/2" sphere from the prototype was 2.59 lbf, while it was 5.22 lbf for the standard VASI 5-9 hand. In order to make the comparison more equitable, refer to the 'Scaled' prototype column. If the prototype hand were able to pinch with 10 lbf, as shown in this column, the pull out force for the 1/2" sphere would be approximately 8.81 lbf. Therefore, if the same 1/2" sphere was grasped by either hand, each pinching at 10 lbf, it would be more difficult to remove the sphere from the prototype hand. It was expected that the 1/2" sphere would be more difficult to remove from the prototype than from the standard VASI 5-9 hand, since the prototype has compliant silicone finger tips under the glove, while the standard VASI 5-9 hand does not. The modified VASI 5-9 hand, however, uses the silicone finger tips and has a value of 6.45 lbf required for pull out of the 1/2" sphere. This is still lower than the 'Scaled' prototype value, but is better than the standard VASI 5-9 hand. There is a possible reason as to why it would be more difficult to remove the object from the prototype. When objects were held by the prototype during the tests, they would sometimes shift towards the end of the test, when there was a lot of force being exerted on them. When this happened, the thumb and fingers would also shift slightly and restabilise the object. The addition of lead shot was halted in these situations to see if the object would slip out. If it did not move for 15 seconds, the addition of lead shot was continued. The shifting of fingers and thumb during tests was possible because the thumb can swivel left to right and the fingers can close independently of one another. This restabilisation was observed often during the pull out tests and it would often stop the slipping action of objects. Nevertheless, with the continued addition of weight, the objects would eventually slip out.

Comparing the results of the 1" sphere for the 'Scaled' prototype vs the standard VASI 5-9 hand, it can be seen that it is 26 percent harder to remove the sphere from the prototype. Compared to the silicone VASI 5-9 hand, it is only 10 percent harder to remove the sphere from the prototype.

The Joiner tests used a 1" thick flat Delrin block as one of the test objects, but it was not available for the prototype tests. Instead, a 7/8" thick flat Delrin block was used. It was assumed that the 1/8" difference in width between the two blocks was small enough so that a good comparison between the prototype hand and the VASI 5-9 hand could still be made. It was observed that 22 percent more force was required to remove the object from the prototype, than from the standard VASI 5-9. However, there was no significant difference in the pull-out force required between the prototype and the silicone VASI 5-9 hand.

There was also difficulty in obtaining a 2" Delrin cylinder, as used by Joiner in his tests, so a 2" acrylic cylinder was substituted for the prototype tests. The results do not correlate as well in this comparison and this is attributed to the differences in surface friction of Delrin vs acrylic. Delrin seems to have a more 'slippery' feel to it than acrylic. Although acrylic is generally much smoother than Delrin, a PVC glove sliding along clean, dry acrylic probably has higher friction. The test results show that it would require 100 percent more force to remove the cylinder from the prototype than from the standard VASI

5-9. Also, the results show that it would require 41 percent more force to remove the object from the prototype, than from the silicone VASI 5-9 hand.

An interesting observation made during the tests was that, the bigger an object was, the more the pull out force required to remove it from a prosthetic hand. The last three objects shown in Table 6.6 were wooden spheres. It was observed that the larger the sphere grasped by the prototype, the more pull out force that is required to remove the sphere. Further, looking at all the 'pull out' forces listed in Table 6.6 for the prototype, it is observed that generally, the larger the object, the more pull-out force that is required to remove it. Upon reviewing the test results of Joiner(26), it was noted that for the results of all cylinder pull-out tests and all sphere pull-out tests, the bigger the object, the higher the pull out force. This was true for both standard VASI 5-9 results, and silicone VASI 5-9 results. The only exception to these observations were his results for the standard VASI 5-9, 1" sphere vs 1 1/2" sphere, where the pull out forces were approximately the same.

6.3.3 Additional Pull-Out Tests

All of the pull out tests performed for comparison with the Joiner results of the VASI 5-9 hand, did not utilise the many of the new features available in the prototype hand. The tests were suited specifically to conventional prosthetic hands and were concerned with the advantages of compliant fingertips. They were not meant to show the advantages of adaptive independent fingers, 'flexing' fingers or a swivelling thumb. In an attempt to test the advantages of these features of the prototype hand, some additional tests were performed.

	Prototype 2.9 lbf pinch Pull Out Force
Secure Grip of 1/2" Delrin sphere	5.24 lbf
Secure Grip of 1" Delrin sphere	Could not be removed with 15 lbf.
Secure Grip of 1 1/4" wood sphere	Could not be removed with 15 lbf.

Table 6.7 Additional Pull Out Tests

Table 6.7 shows the results of these pull out tests, in which the prototype hand would completely envelope the object within its grasp. This enveloping grasp was termed a 'secure' grasp in Table 6.7. By completely enveloping the object, the prototype hand made use of its 'flexing' fingers as well as its adaptive grasp. Objects held in this way were difficult to remove from any direction. The fingers and thumb would virtually form a cage around smaller objects. In the tests conducted and summarised in Table 6.7, the object was 'pulled' upon in the same direction and hand orientation, as the previous standardised pull out tests.

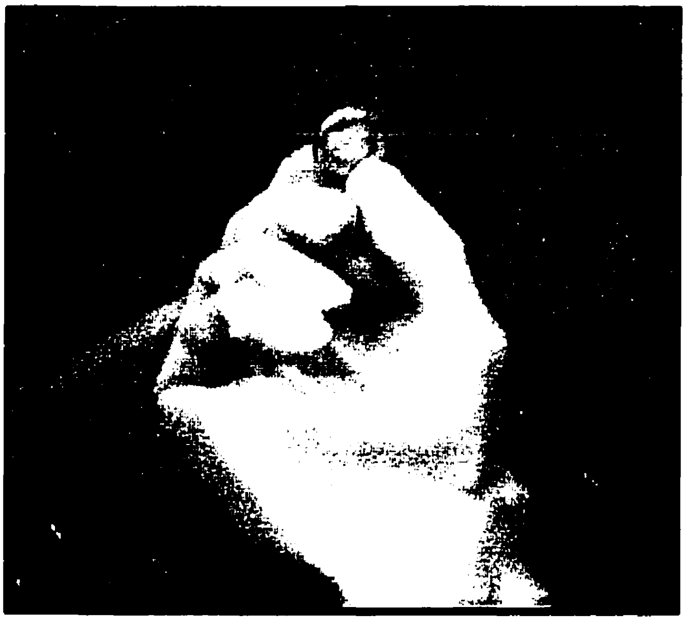


Figure 6.4 Secure Grip of 1 1/4" Wood Sphere

Figure 6.4 shows the 'secure' grasp of the 1 1/4" wood ball that was tested. The results in the table show that the 1/2" sphere required twice as much force to be removed from the prototype when it was 'securely' grasped, as opposed to the grasp results of Table 6.6. In the case of the 1" sphere and the 1 1/4" sphere, the trial was stopped when the hanging basket was loaded with 15 lbs of weight, to prevent the possibility of damaging the fingers. Neither object showed any sign of slipping from the hand and the purpose of demonstrating that a secure grasp could be achieved with only a 2.9 lbf pinch force, had been achieved.

Tests were also performed to observe the effect of objects pulled from the hand while they would twist. This was done by changing the orientation of the object within the grasp. The hook on the end of the object was pointed away from the 'pull out direction line', shown in Figure 6.3. In this way, when tension was applied to the wire, the object would attempt to twist or rotate out of the grasp. The results of these tests were mixed. Sometimes the object would be pulled out of the hand very easily. Sometimes the prototype hand would seem to adapt around the shifting object and hold onto it more securely. In any case, a conventional prosthetic would not be able to do the latter.

6.3.4 Pull-Out Test Summary

It has been shown that it would be more difficult to pull objects out of the prototype hand, if it were able to provide a 10 lbf pinch, than it would be to pull them out of a VASI 5-9 hand, with a 10 lbf pinch. Also, the pull-out results of the prototype hand are slightly better than the silicone finger tip VASI 5-9 hand results obtained by Joiner. This shows that there is some additional benefit in grasping, due to the adaptively independent fingers and swivelling thumb of the prototype hand. It was observed during the pull-out trials that when the object within the prototype's grasp tried to slip out, the prototype's fingers and thumb would shift slightly and maintain the grip. Only after more force was applied to the object, would it finally slip from the hand. It was also observed from the tests that the larger an object is, the higher the pull-out force required to remove it from the hands. This observation was further verified by reviewing the thesis results of Joiner. The reason for this may be that the larger an object is, the more surface contact there is between that object, and a hand. Therefore a higher pull out force is necessary.

Some additional pull-out tests were performed with the prototype, using grasps that would completely envelope the object. With only a 2.9 lbf pinch, the prototype was able to hold objects with 15 lbf applied to them. Similar results may be possible with conventional prosthetics for certain objects, but they may not be able to hold onto objects that try to twist or rotate out of their grip.

Due to the novelty of the prototype hand, there are no standard tests available to test the benefits of its new features. Further testing is recommended to explore some of the potential benefits of the new features.

Chapter 7
Recommendations

7.1 Overview

A number of aspects of the prototype hand design could be improved upon. These improvements include the addition of an automatic two speed transmission, reduction in the *Palm* length, reduction in the time lag during opening, a better cable attachment system, custom finger trajectories, a way of protecting the hand against dirt and moisture and implementation of the ball and socket wrist. The reasons for these improvements is noted, and a method of implementation is suggested. In addition, if the prototype hand is to be mass produced, a few design changes must also be made. These include changing the way the fingers are fabricated, and design of a custom glove specifically for the prototype hand.

7.2 Improvements to the Current Design

7.2.1 Addition of an Automatic Two Speed Transmission

The prototype hand currently has two major deficiencies. Firstly, the pinch force that it can achieve is only about 3.2 lbf, which is approximately one third the pinch force of the conventional VASI 7-11 hand. Secondly, the prototype hand takes 4 to 5 seconds to achieve a full grasp, compared to 1 second for most conventional prosthetic hands. Both of these problems are inter-related and dependent on the gearbox and motor used.

In order to increase the pinch force of the hand, more torque must be generated. Currently, the gearbox used with the hand has a reduction ratio of 22:1 and can yield a maximum torque of 17.66 oz-in. The maximum pinch force that can be produced is proportional to the output torque. In order to have the prototype hand pinch with the desired 9.6 lbf, a torque output of 53.0 oz-in is required from the gearbox. If the same motor is used, a gearbox with a ratio of 66:1 (and a similar efficiency of 73 percent) will be needed. However, if the gearbox is changed to 66:1, the hand would close three times slower than now. It would take 12 to 15 seconds to close, which is unacceptable.

Similarly, in order to increase the speed of closing for the hand, more rotational speed must come from the gearbox. The current gearbox reduction ratio of 22:1 could be changed to a ratio of 7:1 to increase the rotational speed by approximately three times. This would allow the hand to close in 1.2 to 1.5 seconds. However, if the gearbox is changed to 7:1, the hand pinch force would be three times lower than it is now. It would only be able to pinch with approximately 1.0 lbf.

It is not acceptable to recommend that a bigger motor be used. Since most standard DC motors rotate at about 8000 to 10000 rpm, a gearbox of approximately 7:1 would be needed to achieve the 1.2 to 1.5 second grasp. However, the motor torque would have to be nine times higher, to achieve a pinch force of approximately 9 lbf. The only MicroMo motor that could achieve this is a 2342 motor which uses a high energy magnet. However, this motor would draw approximately 9 amps to achieve the desired output torque of 53.0 oz-in using a 7:1 gearbox. The motor would also add 59 grams of weight, above the current weight of the prototype hand motor. This high current and increase in weight would be unacceptable.

The only effective solution is to use a two speed automatic transmission, which would replace the current gearbox. This proposed transmission would have two different reduction ratios. They should be approximately 7:1 for the closing task, and 66:1 during the pinch task. The transmission would change the ratios automatically, by 'mechanically sensing' the output torque at the *Lead Screw*. This could be achieved with a spring loaded switching mechanism. The output torque would be 'mechanically sensed' by a certain amount of deflection by this spring. The system would work as follows. During a close of the hand, the transmission would always start in the 7:1 gear ratio. As it closes, when the output torque rises above 6.0 oz-in (which translates into 1.0 lbf tip pinch force), the transmission would switch to the 66:1 gear ratio. As a note, if 1.0 lbf of pinch is achieved by any of the fingers, that *Cylinder Spring* has gone into Mode C operation, which means the hand is in the fully closed position.

The design of this transmission is quite possible. Otto Bock uses exactly such a two speed automatic transmission in the adult series hands, such as the 7 1/4 hand. The two speeds used in the Otto Bock transmission are unknown. The entire Otto Bock transmission is 12 mm long, 23 mm in diameter, and weighs approximately 20 grams. The current prototype hand gearbox is 11 mm long, 16 mm in diameter, and weighs 4 grams. If an Otto Bock 'like' transmission could be implemented, the length of the current design could remain unchanged, and only an additional 15 grams of weight would be added to the design.

The added benefit of using such a transmission with the prototype hand would be profound. The hand would become usable as a prosthesis, that could effectively compete against the VASI 7-11 and Otto Bock 6 1/2 hands, in terms of performance. There would be no increase in size, a minor increase in weight, and an inevitable minor increase in energy used. As a note, the current energy used by the prototype hand is only 20 to 30 percent greater than the Otto Bock 7 1/4 hand. It is highly recommended that the two speed automatic transmission be adopted.

7.2.2 Reduction in the Palm Length

Currently the *Palm* dimensions of the prototype hand are 80 mm long, 64 mm wide and on average 25 mm thick. The length of the *Palm* is too long and should be around 65 mm in length. The current length was necessary to allow enough room for the translation of the *Cylinder Spring* and the *Piston,* for the hand to achieve a fully independent adaptive grasp.

When the fingers flex, from the fully extended position to the fully flexed position, the entire *Cylinder Spring* translates by 11 mm. In order to allow the fingers to be fully independent of each other, the *Piston* within the *Cylinder Spring*, also translates by this same amount. This gives any finger the ability to fully flex, even if one or more of the other fingers was stopped in the fully extended position. For example, if a grasp was formed in such a way that the index and middle fingers remained fully extended, the current mechanism would allow the remaining fingers to reach the fully flexed position. This is referred to as the adaptive grasp 'range of differentiation'.

The question that arises is, whether or not the fingers need such a large range of differentiation, for adaptive grasp. The prototype hand has been designed and built to allow for the full range of differentiation. However, it has been observed during experiments and many typical uses of the hand, that it never needs the full range of differentiation for adaptive grasp. It is estimated, that the fingers use only half the current flexion/extension range with respect to each other. Only more trials with the hand will reveal how much of a range of differentiation is needed for effective adaptive grasping.

If it is acceptable to limit the adaptive grasp range of differentiation, then a reduction in the *Palm* length of up to 15 mm can be achieved. The *Piston* would only need to travel 6 mm, (from the previous 11 mm) to achieve half the range of differentiation. This results in a 5 mm reduction in the *Palm* length. By reducing the *Piston* travel, there is an additional 5 mm to 7 mm reduction in the *Compression Spring* length. The reason for this, is that the current *Compression Spring* needs to be 23 mm in uncompressed length

(12 mm fully compressed) to be able to compress the required 11 mm. However, if only a 6 mm compression is required (to achieve half the range of differentiation), the spring would not need to be so long. The overall length of the spring could be as low as 13 mm and the fully compressed length could be 7 mm.

Therefore, a total savings of 10 to 12 mm in the length of the *Palm* can be achieved by limiting the adaptive grasp. Further, the current *Cylinder Spring* mechanisms are not connected to the *Force Plate* in a very effective way, in terms of length. With a design optimisation, a further 4 to 5 mm can be saved at the connection point. Therefore, the overall length of the *Palm* could be made to fit within 65 mm.

7.2.3 Reduction in Time Lag During Opening

Another major problem with the prototype hand, is the time lag that occurs during the opening of the hand. For the first 1 to 1.5 seconds after the open command is issued, there is no apparent motion in the hand. This opening lag could be confusing to a first time user, since he would be issuing the open command and there would be no visible motion of the prototype hand for this period of time.

The time lag actually occurs for both closing and opening of the hand, for equal times. During closing, it occurs after the hand forms a pinch because the *Pistons* in the *Cylinder Springs* must 'bottom out' or reach Mode C, for the final pinch to form. The *Pistons* cannot reach Mode C immediately on formation of the pinch, because they must travel a specific fixed distance (11 mm) to reach Mode C. This physical travel distance (or length) was machined into the *Cylinder Springs*, so that a maximum adaptive grasp range of differentiation could be achieved, as described in Section 7.2.2. Unfortunately, if the hand attains a pinch position before the full 11 mm has been travelled by the *Pistons*, the balance of the distance must be travelled during what appears to be a closing time lag. During opening, this net distance is travelled again by the *Pistons*, but in the reverse direction, during what appears to be an opening time lag.

There is no easy way to fix the time lag problem. The time lag is inherent in the design of the Cylinder Spring Adaptive Grasp System. However, the time lag could be greatly reduced for a majority of grasps, by reducing the 11 mm *Piston* travel distance, by 2 to 3 mm. Currently, the *Cylinder Springs* need 11 mm of travel to produce a full adaptive grasp range of differentiation. However, only 8 to 9 mm of travel is done by the *Pistons* upon formation of an average tri-digital pinch. Therefore, the net difference of 2 to 3 mm, which is only used in the adaptive grasp of highly irregular objects, is constantly creating time lag for adaptive grasp of regular objects.

By reducing the travel range of the *Pistons* by 2 to 3 mm, the time lag could be greatly reduced, at the expense of also reducing the adaptive grasp range of differentiation.

7.2.4 Improving Cable Attachment

The prototype hand uses a Kevlar cable which is looped through the *Thumb Cylinder Spring* at one end and looped through the *Link 4T Slot Pin* at the other end. This doubles the cable along the path and theoretically reduces the tension on the cable by one half. Currently a knot is used to tie the two ends of the cable into a loop. This method works well, but it is difficult to control the length of the loop when tying knots.

The cable loop length is very important in the design, because it has a tremendous influence on the finger tip to thumb tip alignment, during a pinch. Therefore, if the cable needs to be replaced, it becomes a great challenge to tie a knot that will bring it to the correct loop length.

The knot used it is a double knot that will not slip when excessive tension is applied. It is created as follows. First, an ordinary knot is tied into the cable, then another ordinary knot is tied around the pin on the *Cylinder Spring*. When the knot around the pin tries to slip, the first knot tied into the cable will not be able to slip through the knot around the pin. Although the knots do not slip, they do tighten, increasing the loop length by up to 1 mm. The knots work well, but it is very tedious to use them. Previous to the knot system, a set screw was screwed tight onto the cable to secure it. Although this method allowed for precise control of the cable length, it caused damage to the cable. The tip of the set screw would fray the strands of the Kevlar cable, causing the cable to break.

A design using an aluminium piece that can be crimped onto the cable should be investigated. The aluminium piece could have a hole drilled through it so that the pin in the *Cylinder Spring* could pass through it. In order to prevent the Kevlar cable from slipping through the aluminium, a knot can be tied into the cable, as before. Since this process can be done before installation, the loop length can be controlled easily. If fine tuning of the finger tip to thumb tip alignment is necessary after the new system is implemented, this alignment can always be done by adjusting the screw depth of the *Piston* on the *Force Plate*, as explained in Section 5.3.

7.2.5 Custom Finger Trajectories

It is currently not known if the finger tip trajectories of the prototype hand are sufficiently suitable for most tasks, or if they will need optimising. It was explained in Section 3.3 that it is possible to customise finger tip trajectories. This can be done by replacing the *Straight Slot* that the *Link 6 Slot Pins* currently travel in, with a curved slot. The curve will have to be defined in such a way that it produces the desired tip trajectory. This can be done with the aid of simulation programs such as Working Model 2D. Only further tests with the prototype hand will reveal if customised finger tip trajectories will be necessary.

If custom tip trajectories are found to be needed, they could be implemented in one of two ways. The curved slot could be permanently machined into the Delrin *Palm*. This would allow for easy manufacture, since the process would be the same even if the slots were straight. Also, different versions of the *Palm*, with differing curved slots, could be created for users with different needs. The other way to create the curved slots would be to use one standard *Palm* design, with replaceable inserts. These inserts would have the curved slots machined into them, however, this would increase the number of parts and the fastening complexity.

7.2.6 Protecting the Hand from Dirt and Water

The prototype hand has been designed in a versatile way. Because there are no motor or electronics anywhere within the hand below the wrist, the hand is very tolerant to water penetration. None of the components would be immediately affected by water and if necessary, the hand and wrist could operate while completely submerged. However, corrosion would become a problem with the current hand if it is repeatedly subjected to moisture.

In addition to water, other common contaminants are dirt and sand. The fingers happen to be designed in such a way that they are 'self cleaning' and would eventually expel any sand within their links as they move. The *Cylinder Spring* mechanisms are fairly well sealed and it would be very difficult for dirt or sand to enter. Nevertheless, the clearance in the hole between the *Piston* and the *End Cap* of the *Cylinder Spring*, as shown in Figure 4.4, could be reduced to a tighter tolerance. The real problem for entry of dirt or sand into the *Palm*, is the contamination of the *Lead Screw* and *Ball Nut*. This problem was discussed at length with one of the engineers from the Ball Screws and Actuators company(29). Sand or dirt will temporarily increase the friction between the *Lead Screw* and *Ball Nut*, resulting in rough operation until the balls within *Ball Nut* crush the sand down. The abrasive action of the sand will wear down the *Lead Screw* slightly. If the

Lead Screw assembly is continually subjected to sand, its life time will be decreased tremendously.

To protect the hand from water related corrosion, it is recommended that any steel components currently used within the hand be replaced with stainless steel. These components would be the roll pins used in the finger links, the needle roller bearings, the compression springs, nuts and bolts and the *Lead Screw*. Most of the nuts and bolts in the current prototype are already stainless steel. The manufacturer of the *Lead Screw* noted that a stainless steel version of the *Lead Screw* was available, but that the cost would be greater. Switching the remaining elements to stainless steel would be fairly inexpensive and simple. All other elements in the hand are unlikely to corrode.

To protect the hand from dirt and moisture, it is recommended that a double glove design be implemented. This design could be similar to the approach used by the Otto Bock adult series hands. Although it would be possible for the outer glove to tear, it would be more difficult to tear both gloves simultaneously. The use of two gloves may also increase the compliance of the fingers. This compliance and the sliding action between two lubricated gloves may reduce the chance of simultaneous penetration of both gloves. It is recommended that investigations of the Otto Bock double glove system be done to determine if that system is less likely to be penetrated by the elements, than a single glove system.

Finally, if the hand is severely contaminated with dirt after an incident, the glove could be removed and the hand and wrist could be washed with water in the sink, without disassembly. If the stainless steel conversions were made, the hand would be unaffected. Excess water could be removed with a hair dryer.

7.2.7 Implementation of a Ball and Socket Wrist with U-Joint

The current prototype hand does not have a ball and socket wrist unit. A wrist unit capable of rotation only, can be implemented on the current hand. In a recent survey, the ability of the wrist to flex, extend, adduct, abduct and rotate is considered to be important to users of prosthetic devices(1). More specifically, the report shows that for users of electric powered prosthesis, the importance of wrist movement is high. The only items of higher priority that were noted, can already be achieved by the prototype hand, such as fingers that can curl, a thumb that can curl and adduct/abduct. Therefore, the next step in improving the functionality of the prototype hand, is to implement a ball and socket wrist unit. Such a device would reduce awkward body compensatory motions that are usually performed by the use of a less functional wrist.

7.2.8 Custom Energy Saver

A custom energy saver should be created for the prototype hand. This would maximise the usefulness of the MicroMo 1724E motor, which is capable of a stall torque of 1.49 oz-in. By currently using the VASI 5-9 B energy saver with the prototype, the output torque is limited to about 1.1 oz-in, which under utilises the motor. It is recommended that the new energy saver have a current cutoff value of approximately 1600 mA. This would increase the final pinch force of the hand by 25 percent, to around 4.2 lbf. As explained in Section 6.1.3, this added increase in pinch force would only consume a small amount of additional energy.

7.3 Mass Production Issues

If the prototype hand becomes a commercial device, it may need to be mass produced. As such, two issues arise regarding the manufacturability of the fingers and the design of a glove customised for the prototype hand.

7.3.1 The Finger and Thumb Links

The current method of machining the finger and thumb links from aluminium is very labour intensive. It is estimated that an experienced machinist would take 50 to 60 hours to machine the finger and thumb pieces. The going rate for machine shop time is $50 to $60 per hour and therefore the cost of machining these pieces becomes prohibitive.

The links have been designed with the intent of using 7075 T6 aluminium to take the design forces, assuming the hand is capable of a 9 lbf pinch. During the Ideas 5.1(22) stress simulations, it was found that the areas closest to the pin holes for Link 1 and Link 6 experienced the most stress. These maximum principal stress values were approximately 5 to 10 times below the ultimate tensile strength of the material, which is 83,000 psi (5.72×10^8 Pa). The shear stress results were approximately 10 times below the ultimate shear strength, which is 43,000 psi (2.96×10^8 Pa). The aluminium was chosen because it was strong, rigid, lightweight, resistant to wear and easy to machine.

In order to reduce the cost of creating the finger and thumb links, it is recommended that a plastic injection molding system be investigated. The plastic material must be very strong, very rigid, tough and resistant to wear at the pin holes. A technology now exists whereby injection molded plastic parts can be impregnated with fibres. The resulting matrix is strong and lightweight. There also exist injection molding technologies whereby a metal core can have plastic injection molded around it. If a plastic cannot be found that is strong enough for the application, die casting the finger links from aluminium should also be investigated.

The fingers have six links each, which are the same for each finger, and the thumb has four more links. Therefore a total of 10 unique molds would be required for injection molding or die casting. The cost of each mold is unknown since an exact quotation would be necessary. Also, the market for the hand, that is, the number of hands to be produced is also unknown. Therefore, it is recommended that the market for this hand be researched, and based upon this, the cost of injection molding the links be investigated.

7.3.2 The Glove Design

A glove should be used with the prototype hand for two reasons. It protects the hand from the elements and is considered to make the hand look more cosmetic. Unfortunately, conventional gloves have three major limitations. They were not made to allow for curling fingers, adduction or abduction of the thumb and they do not fit well near the pinky finger. Heating a glove and stretching it over the prototype hand is a delicate task and is difficult to do without tearing the glove. Even if stretched successfully, the glove will eventually tear near the base of the pinky or base of the thumb.

A custom glove design is needed with 'corrugations' at the knuckle joints of the fingers and around the base of the thumb. Also, the glove must be made to fit the pinky finger better. These corrugations would act in a similar way to the skin on a natural hand. When the fingers of a natural hand are extended, the skin gathers into 'rolls' at the locations of the joints. Also, when the thumb of a natural hand is adducted or abducted, gathering of the skin occurs around the carpometacarpal phalanx.

There are no conventional prostheses that have fingers which can curl during flexion or have a swivelling thumb, and therefore, there are no conventional gloves made to withstand these types of stresses. It is known that the Montreal Hand could not use a conventional glove(7). No glove was used with the Southampton Hand or the Belgrade/USC Hand, and it is known that creators of the Utah/MIT Dextrous Hand originally intended to use a glove(17), but eventually abandoned the idea. If the prototype hand or one of the other experimental hands is to be seriously considered as a prosthetic device, a glove will have to be designed. Although it is possible to heat, stretch and patch a conventional glove for use with the prototype hand during testing, such a procedure would be prohibitive for a mass production, commercial application.

Development of a glove could be done in collaboration with the manufacturers of the existing conventional gloves. A new glove material may or may not be needed. The inner glove of the Otto Bock adult hands has corrugations in it, however, the technology to create corrugations in the knuckle areas of the glove will need to be developed further. It seems at present, that conventional gloves are simply inadequate for adaptive grasp experimental hands.

Chapter 8
Conclusion

8.1 Objectives Satisfied

A prototype hand has been created that meets the objectives of this thesis, as listed in Section 2.3.3. The hand is roughly sized for children in the 7 to 11 year age group. It has five digits, each of which curl as the digit flexes and straightens out as the digit extends. This feature, together with the *Cylinder Spring* mechanism, give the hand the ability for passive adaptive grasp. The thumb can be passively adducted or abducted by the able hand of an unilateral amputee user. A compliant layer of silicone has been added under the digit tips and on the underside of the digits. Finally, the hand has been designed with a u-joint connector, in such a way that the design will more easily facilitate the implementation of a ball and socket wrist.

Therefore, the major contributions of this work have been the following. The curling digit design, the *Cylinder Spring* adaptive grasp mechanism design, and the adduction/abduction thumb design. However, the most important contribution was combining them in such a way that the prototype hand is smaller and lighter than any other experimental hand in its class.

8.2 Supplemental Designs

During the design of the prototype hand, a number of possible design directions existed. Some of the designs that were not followed have been included with this work, as a reference for future design work on hands similar to the prototype hand. Based on the literature searches done in Chapter 2 on other experimental hands, there is a very limited amount of material that exists to help with the design of these hands. Chapter 3 gives important explanations of why some designs failed, so that the same mistakes are not repeated. Similarly, with further modifications, some of these designs could be made to function within hands of different requirements. It is hoped that this information will serve to increase the knowledge and tools available to other designers of multi-fingered, adaptive grasp hands.

8.3 The Prototype Hand Design

The hand as designed and built has attempted to incorporate a number of challenging design elements. Specifically, the flexion/extension finger design, the adaptive grasp mechanism design and the combination of flexion/extension and adduction/abduction thumb design have all been very challenging aspects to this project. Fitting all three devices within the hand and keeping it small was difficult. As a result of some of these challenges, compromises were made between all design elements, so that the system was more balanced. What has resulted in mechanical terms, is a solid first attempt at creating a small multi-fingered, adaptive grasp hand.

8.4 Testing and Results

Bench tests were performed with the prototype hand in an attempt to determine how effective the design is compared to conventional prosthesis. Electrical current observations were made on the prototype hand and on other conventional prosthesis. The information learned was very valuable as it gave an accurate placement of the hand with respect to conventional prosthesis. This is important because the prototype hand will be competing against these hands if it is to be commercially produced. Data analysis has revealed that the prototype hand is too slow and consumes 3 to 5 times more energy than conventional hands. Also, pinch force testing shows that the prototype hand can only exert a maximum pinch force of 3.2 lbf. This is approximately one third to one quarter of what conventional prosthesis in the same age category are capable of. Finally, pull-out testing showed that the prototype hand produced similar 'scaled' results to the silicone compliant VASI hand tested by Joiner(26). However, the pull-out tests performed were done with limited trials and only a limited number of identical test objects were used.

More bench testing is required with the prototype hand. One question that must be investigated further is whether or not the prototype hand needs to pinch as hard as a conventional prosthesis. It was hoped that some of the new design features may have increased object grasp stability, such as the adaptability or the compliance of the fingers. These issues must be investigated further. Also, proper testing methods will have to be developed to test for increased grasp stability and increased function, as no current test methods exist.

8.5 Recommendations

A number of recommendations have been made to address some of the existing problems with the prototype hand. Some of the recommendations made would require a substantial amount of work. Nevertheless, they have been suggested because it was felt that the design would greatly benefit from their application. In addition, some recommendations have been made regarding the mass manufacture of the hand. Of course, the hand is nowhere near the mass production stage, however, these recommendations are made now so that a direction can be given for future design work. For example, a new construction process should be considered for the manufacture of the fingers, since the current method would be long and costly.

8.6 Future Work

The prototype hand is novel and has new features that are not available with conventional prostheses. Currently, one can only conjecture about how useful these new features really are. Bench tests can provide only some of the answers. Testing with amputee subjects will provide many more answers. This type of testing was done with the Montreal Hand. If some of the recommendations suggested in Chapter 7 can be made, it is recommended that the prototype hand also be tested in long term trials, to try and uncover any potential problems or any new advantages.

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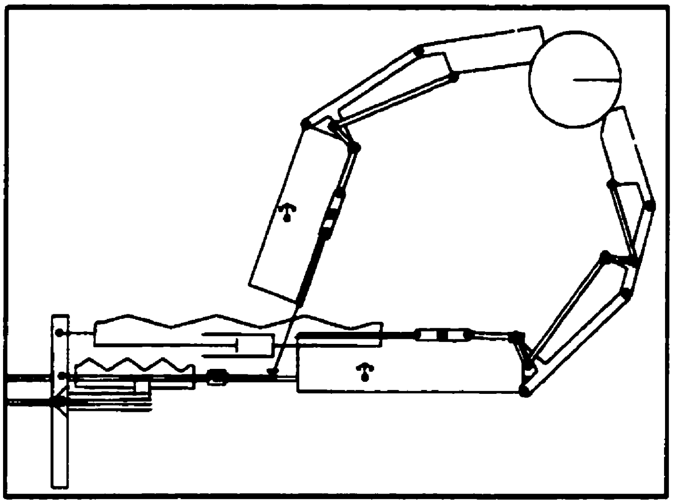
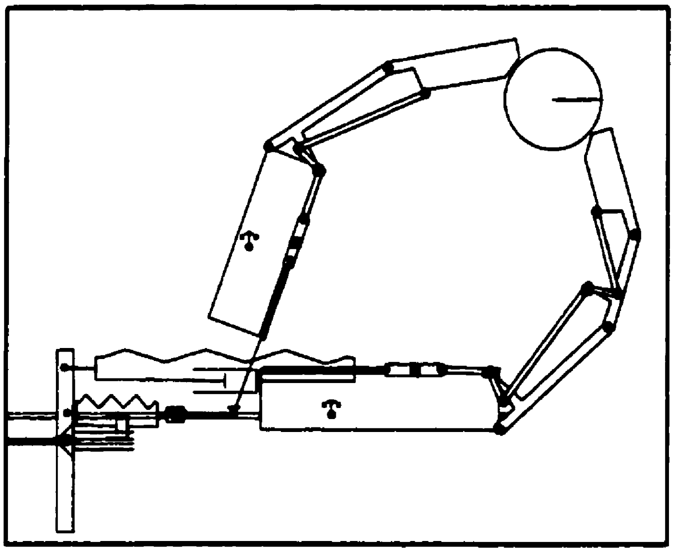
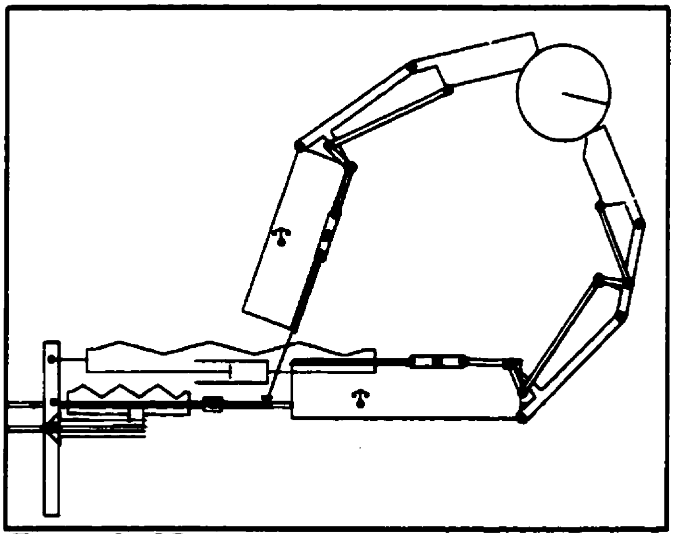
Appendix A.1:
Unstable Pinch Simulation, using Spring Adaptive Grasp System:



Frame 1 of 5

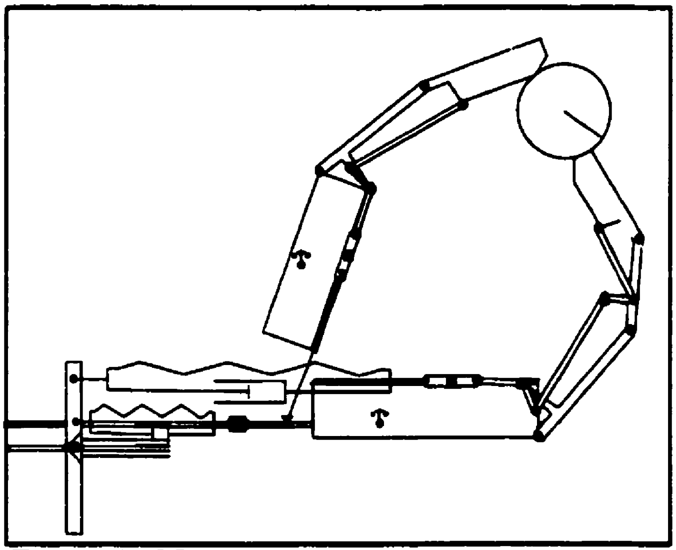


Frame 2 of 5

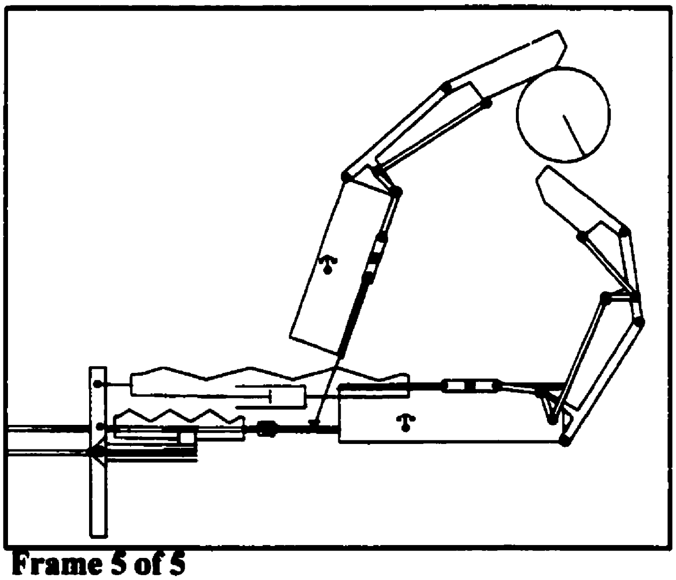


Frame 3 of 5

Appendix A.1:
Unstable Pinch Simulation, using Spring Adaptive Grasp System(Continued):



Frame 4 of 5

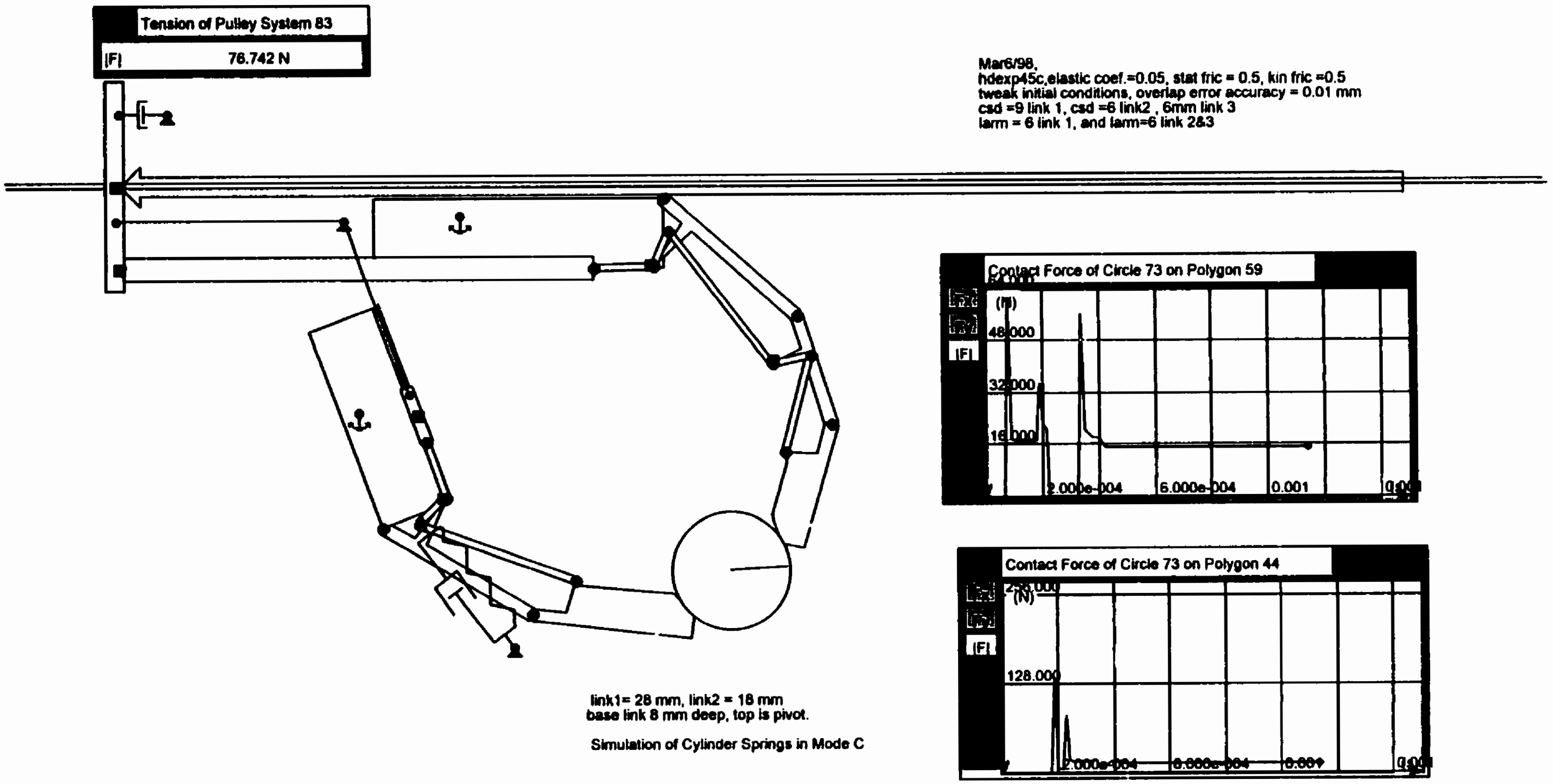


Frame 5 of 5

Appendix A.2:

Typical Pinch Simulation using Working Model:

Appendix A.2:
Typical Pinch Simulation using Working Model



Tension of Pulley System 83

|F| 76.742 N

Mar6/98,
hdexp45c,elastic coef.=0.05, stat fric = 0.5, kin fric =0.5
tweak initial conditions, overlap error accuracy = 0.01 mm
csd =9 link 1, csd =6 link2 , 6mm link 3
larm = 6 link 1, and larm=6 link 2&3

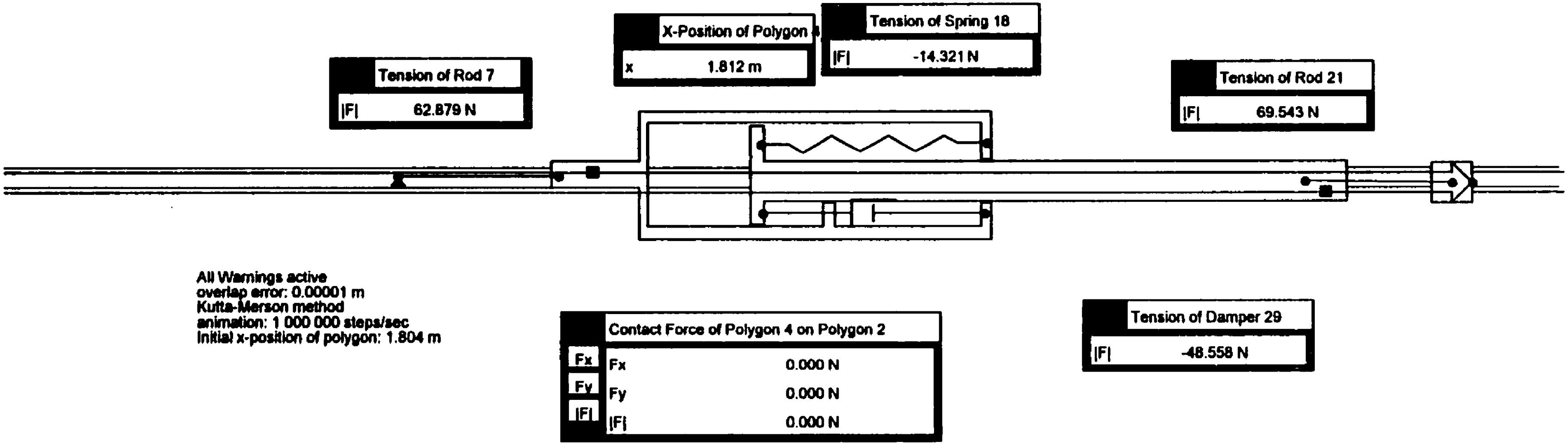
Contact Force of Circle 73 on Polygon 59

Contact Force of Circle 73 on Polygon 44

link1= 28 mm, link2 = 18 mm
base link 8 mm deep, top is pivot.

Simulation of Cylinder Springs in Mode C

Appendix A.2:
Typical Simulation of Cylinder Springs



Tension of Rod 7
|F| 62.879 N

X-Position of Polygon
x 1.812 m

Tension of Spring 18
|F| -14.321 N

Tension of Rod 21
|F| 69.543 N

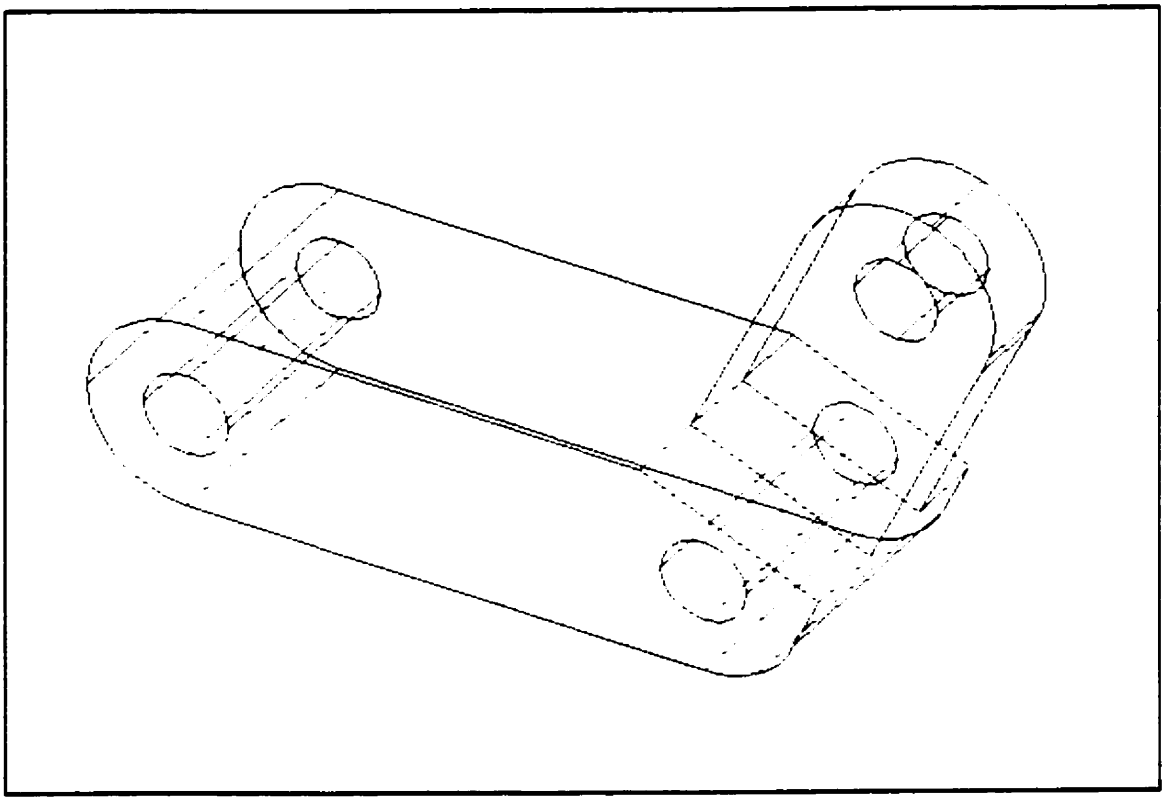
All Warnings active
overlap error: 0.00001 m
Kutta-Merson method
animation: 1 000 000 steps/sec
Initial x-position of polygon: 1.804 m

Contact Force of Polygon 4 on Polygon 2
Fx 0.000 N
Fy 0.000 N
|F| 0.000 N

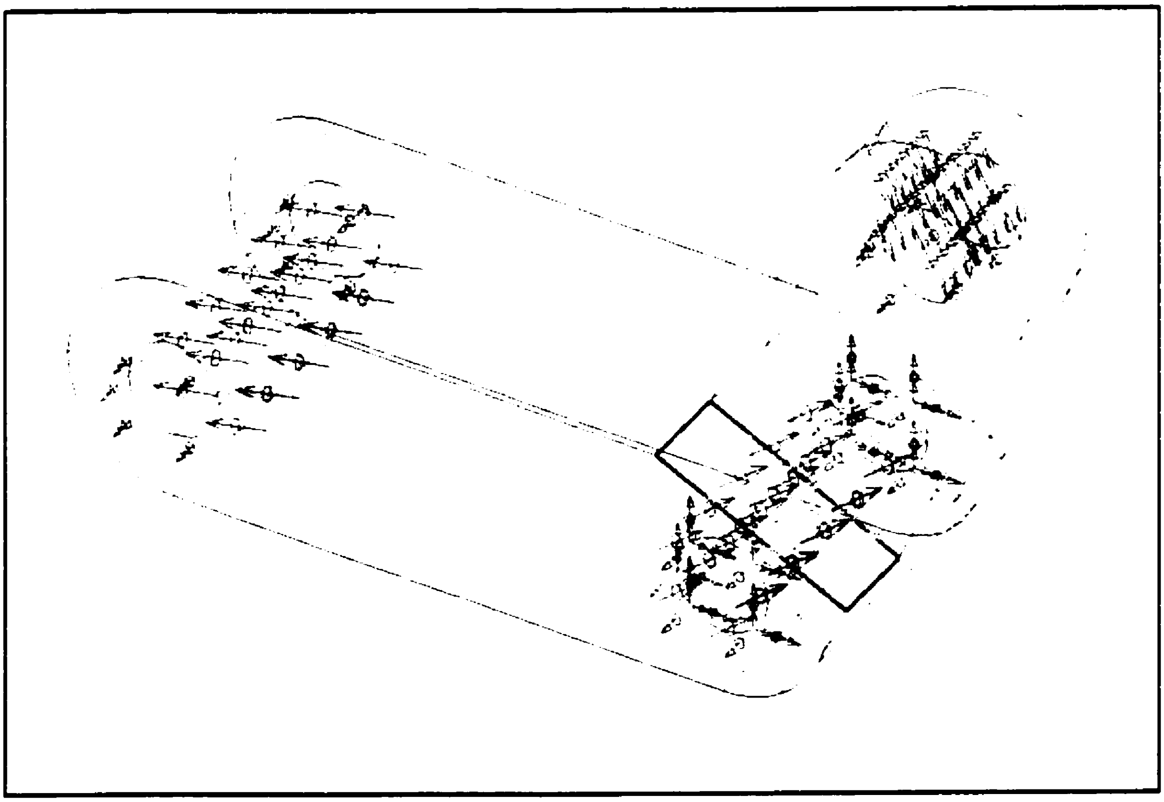
Tension of Damper 29
|F| -48.558 N

Appendix A.3:

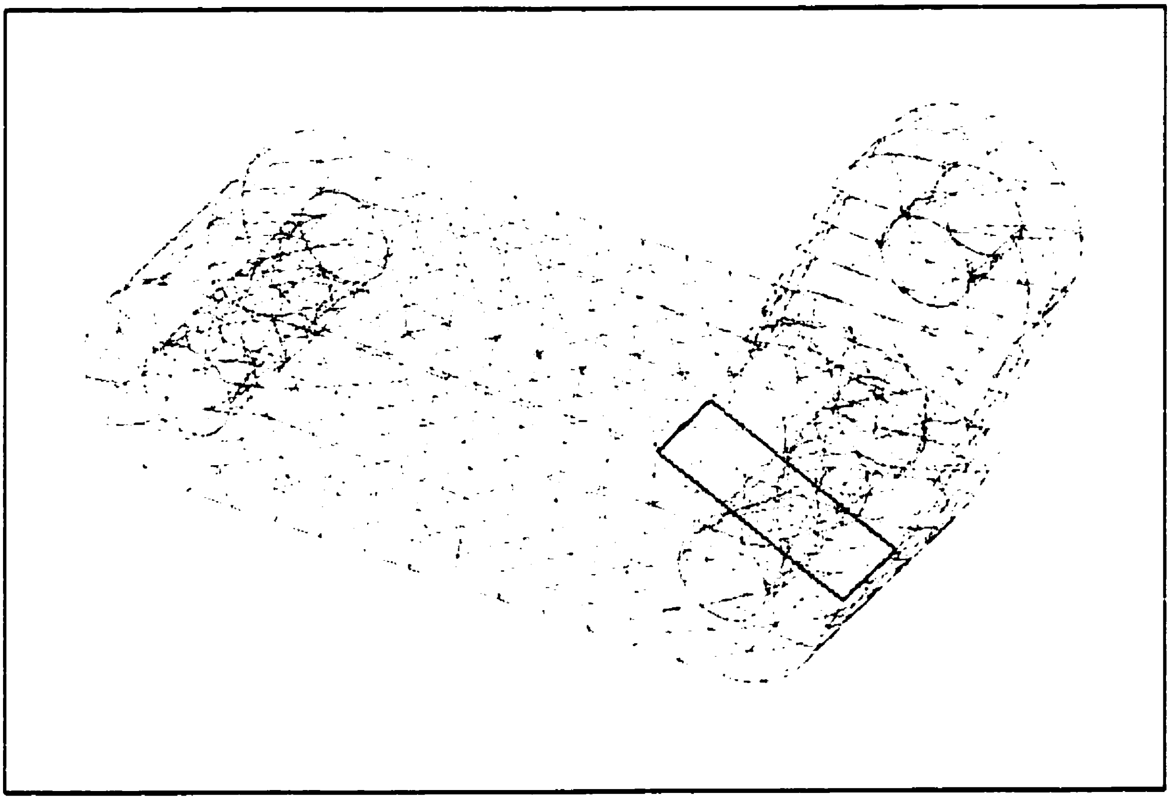
Ideas 5.1 Simulations results for Link 1 & Link 6:



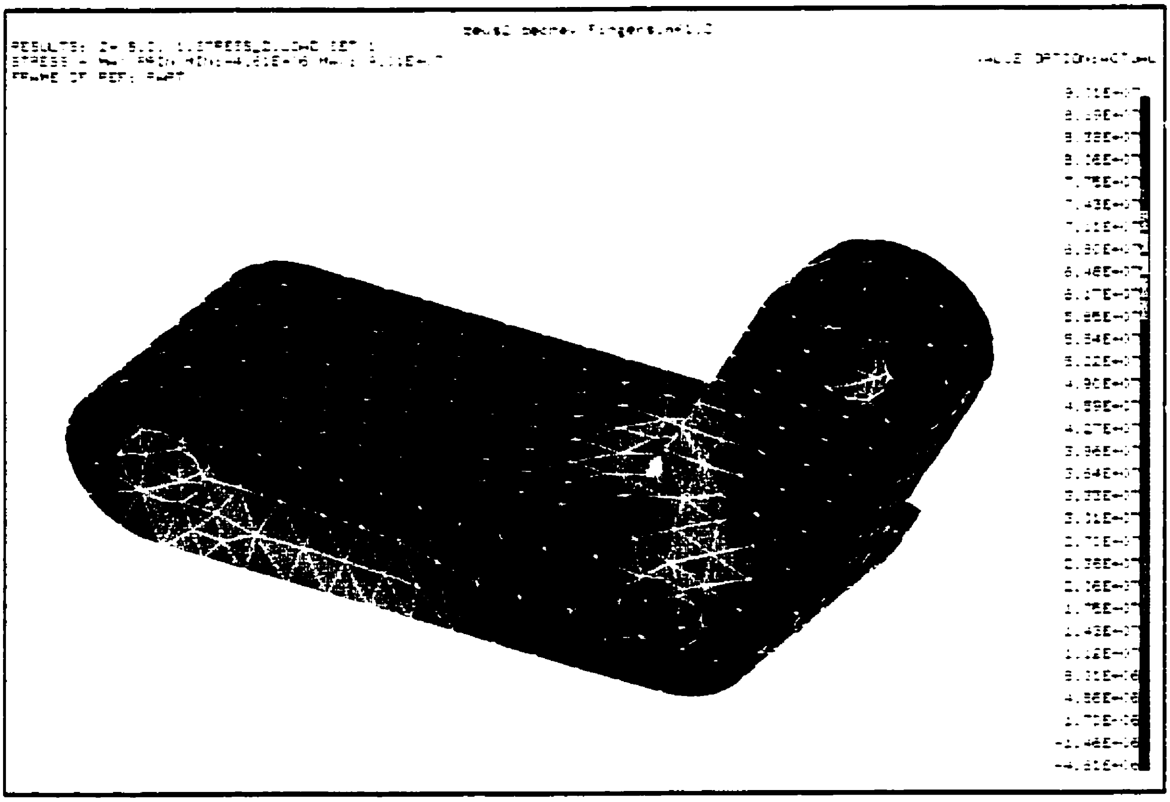
Link 6 Wireframe



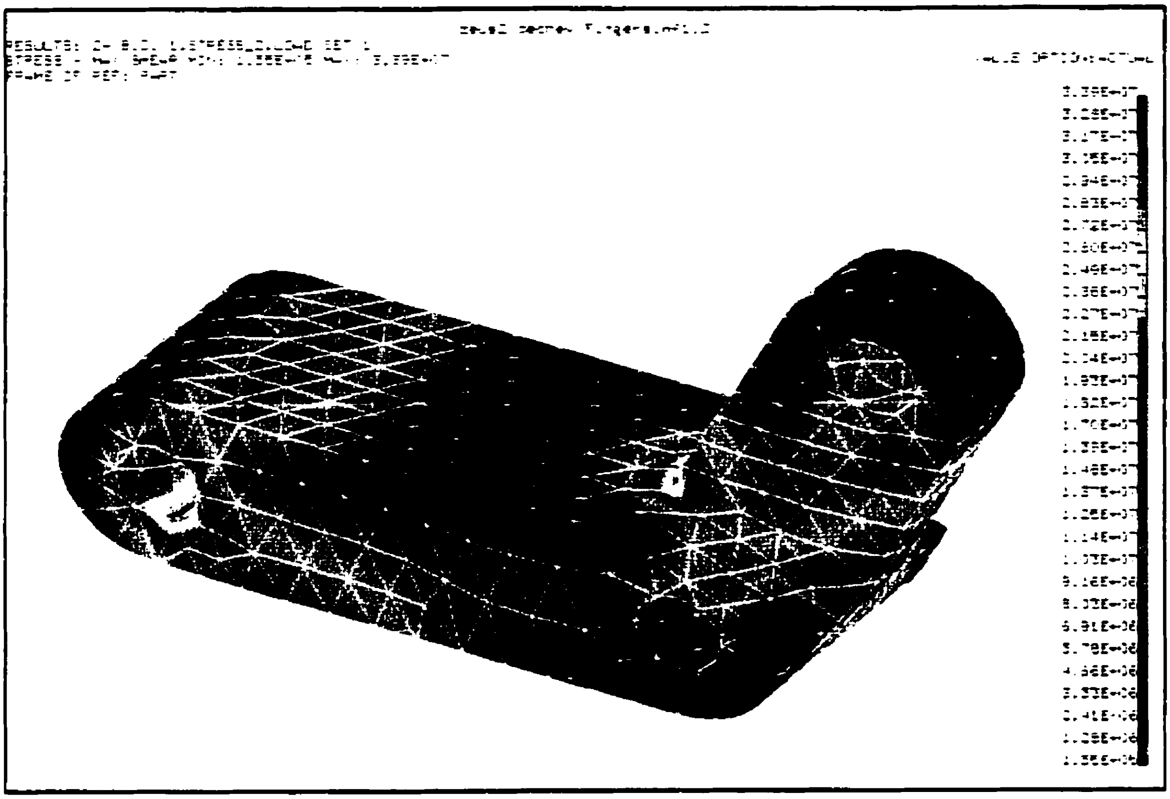
Link 6 Loads and Constraints



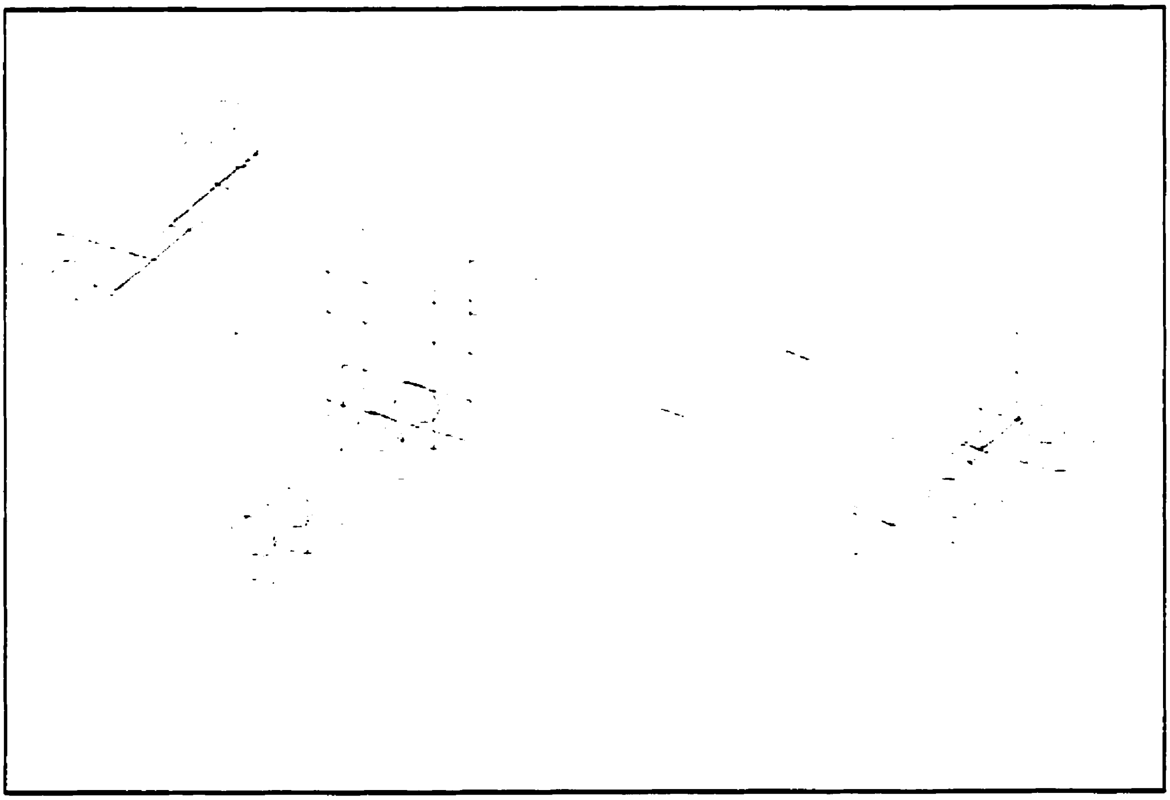
Link 6 Solid Mesh, (3375 elements, 5698 nodes, 0.75 mm element size)



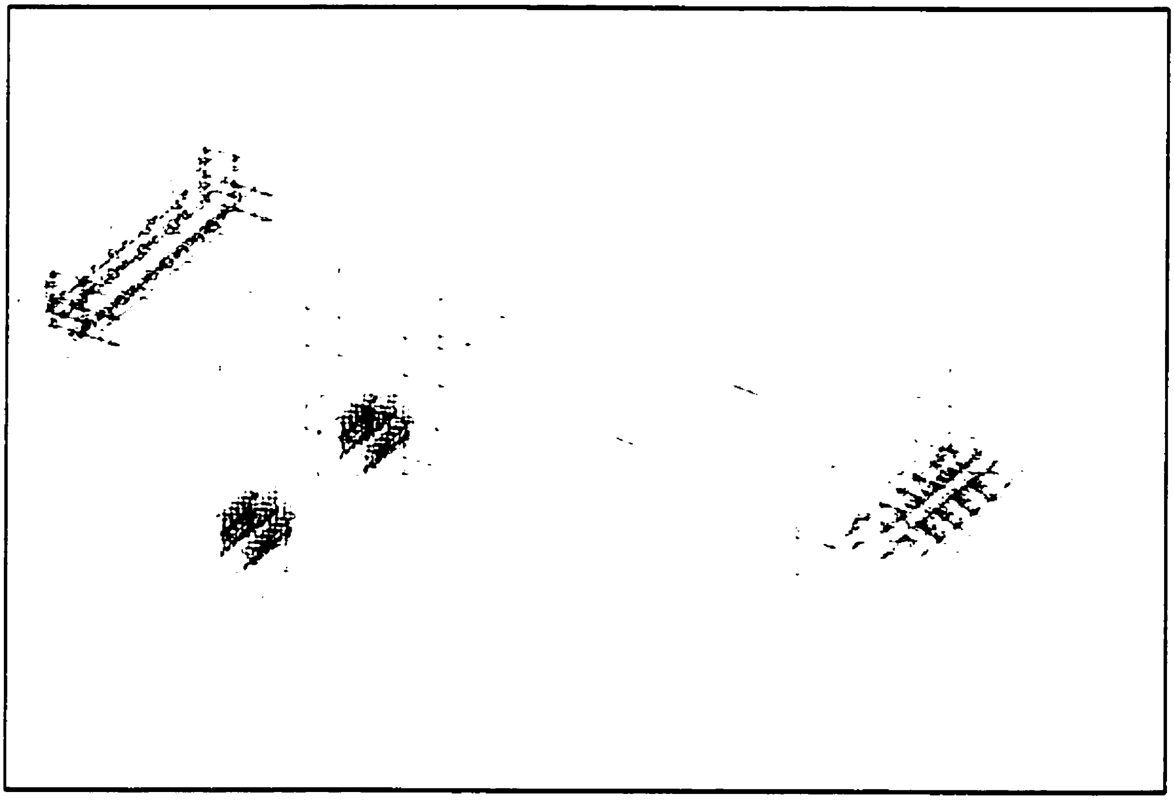
Link 6 Principal Stress Results



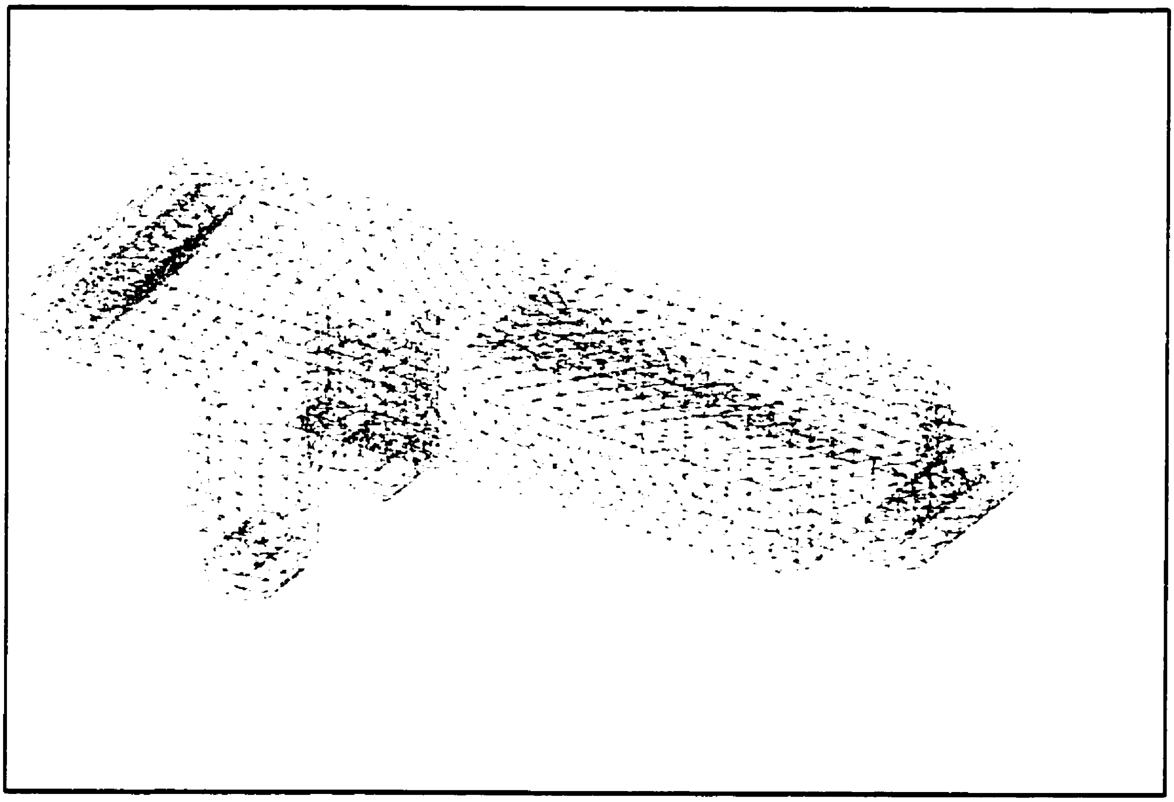
Link 6 Shear Stress Results



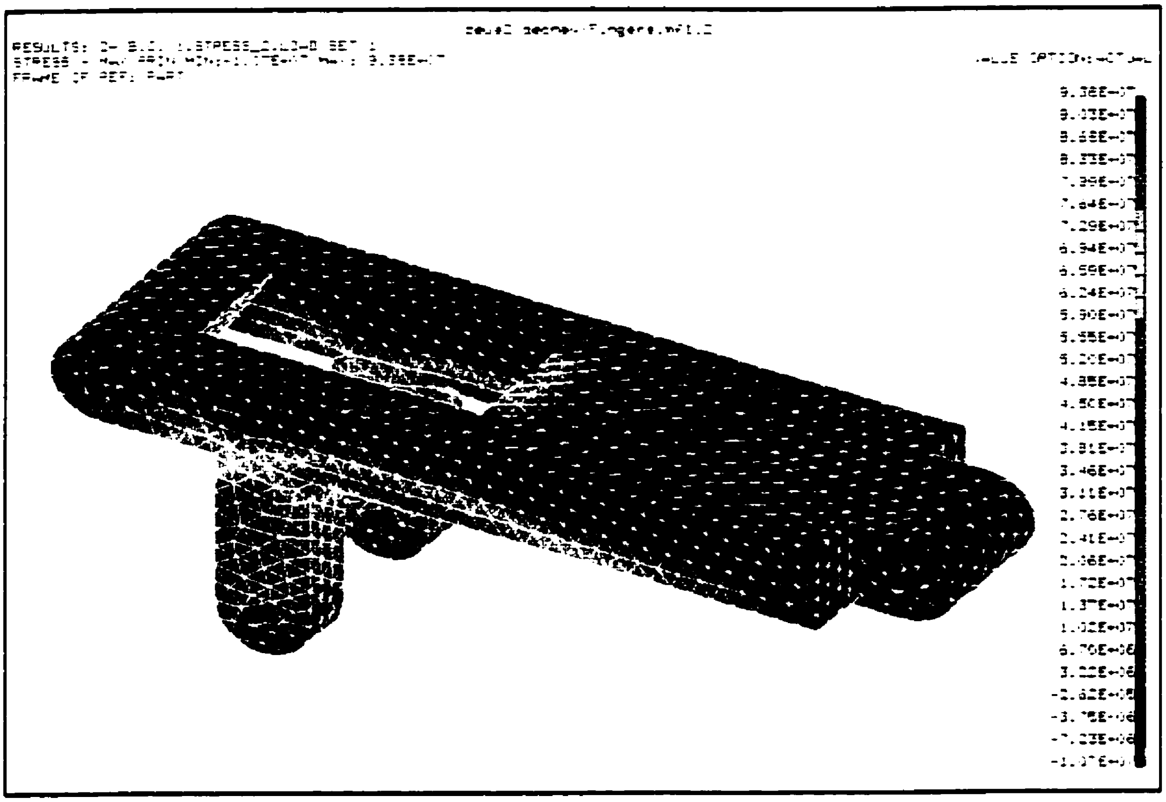
Link 1 Wireframe



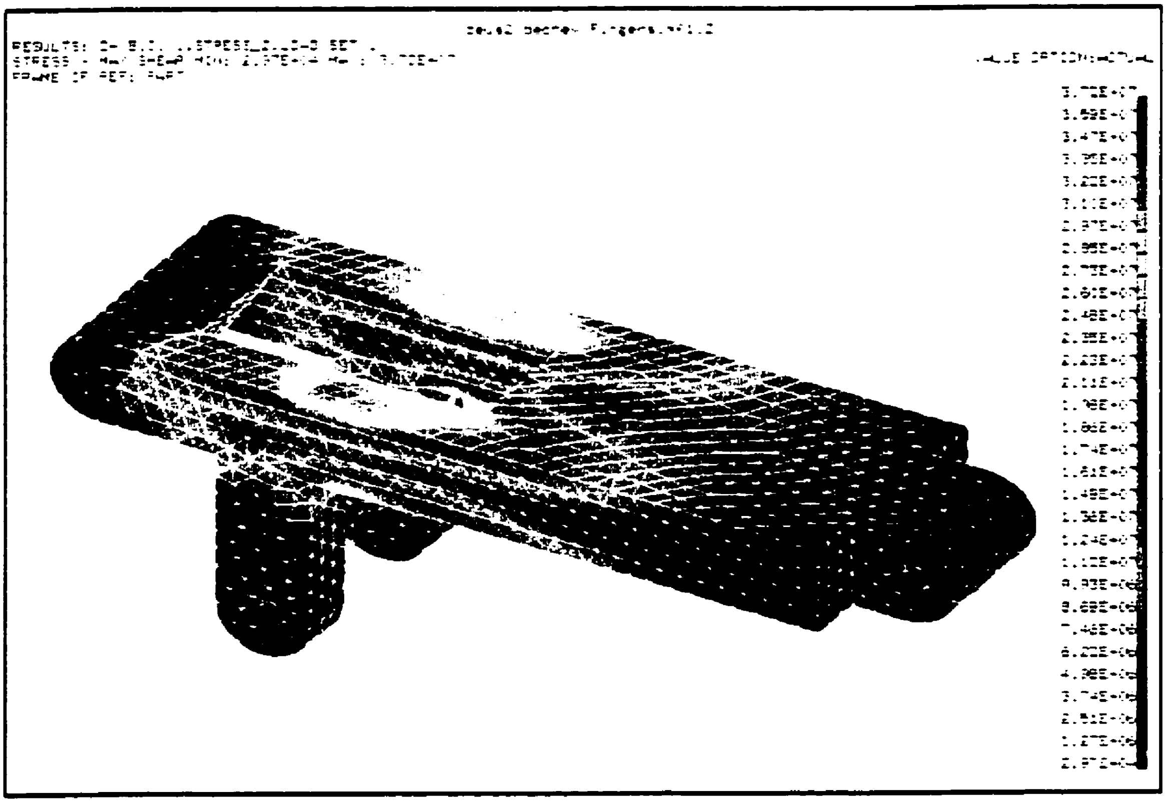
Link 1 Loads and Constraints



Link 1 Solid Mesh (11684 elements, 3048 nodes, 0.75 mm element size)



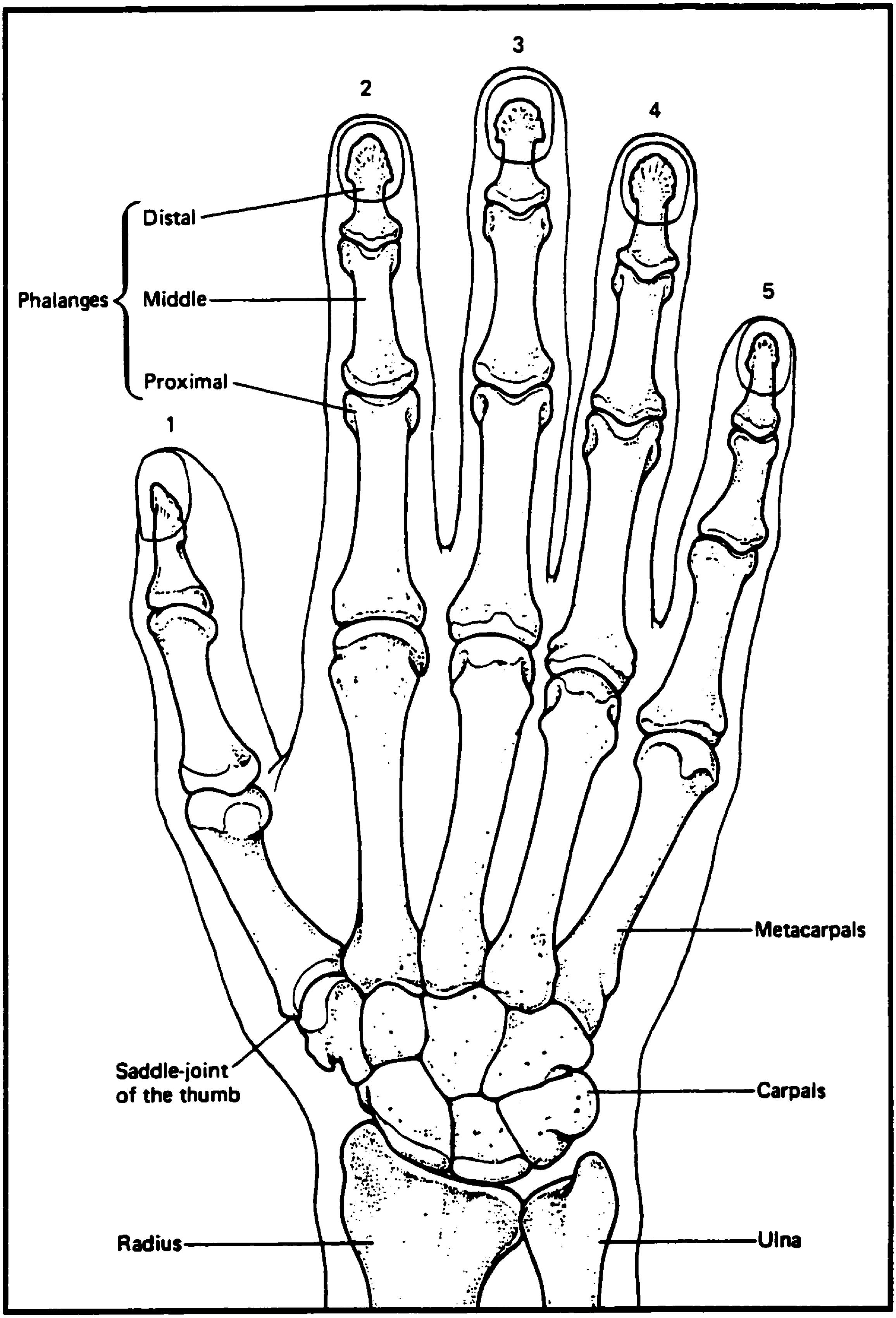
Link 1 Principle Stress Results



Link 1 Shear Stress Results

Appendix B:

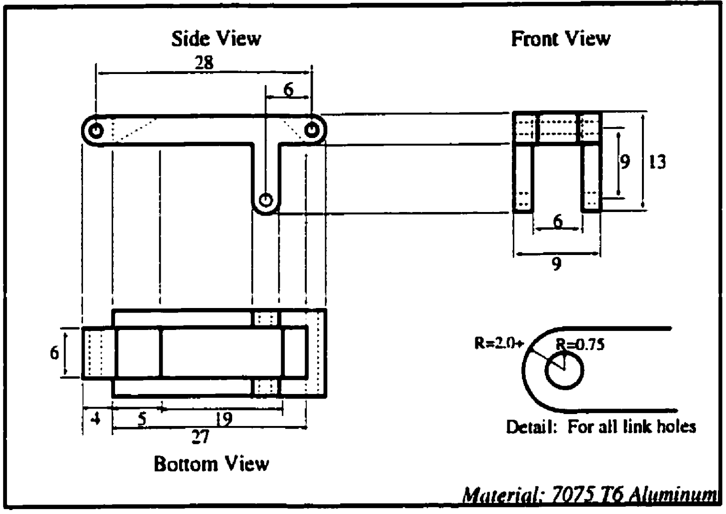
Labelled Bone Diagram of Hand(30):



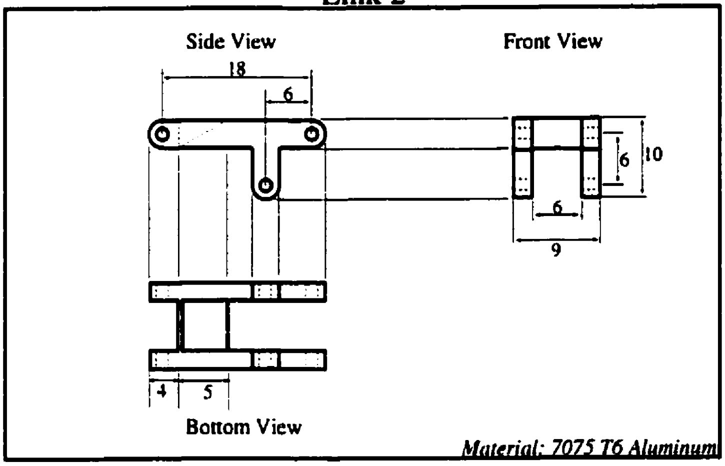
Appendix C.1:

Finger Link Drawings:

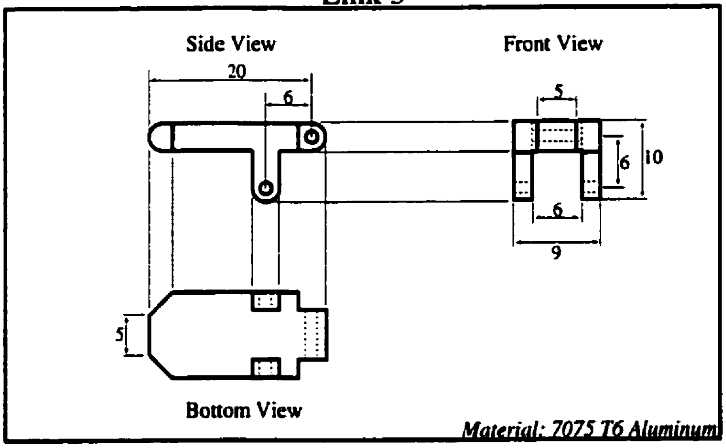
Link 1



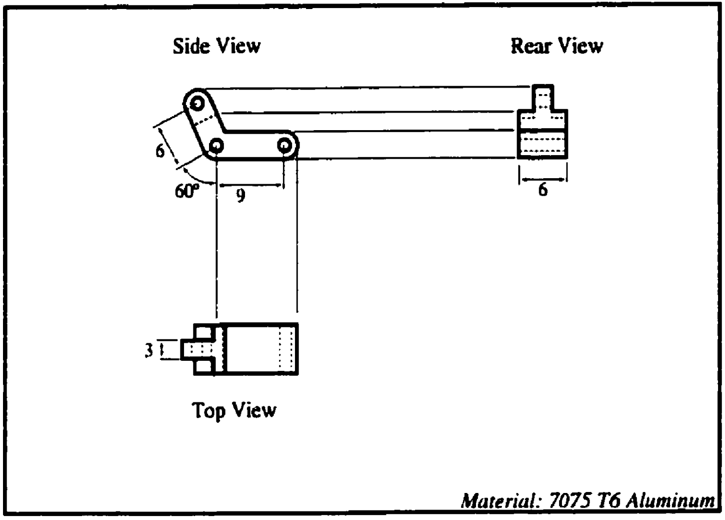
Link 2



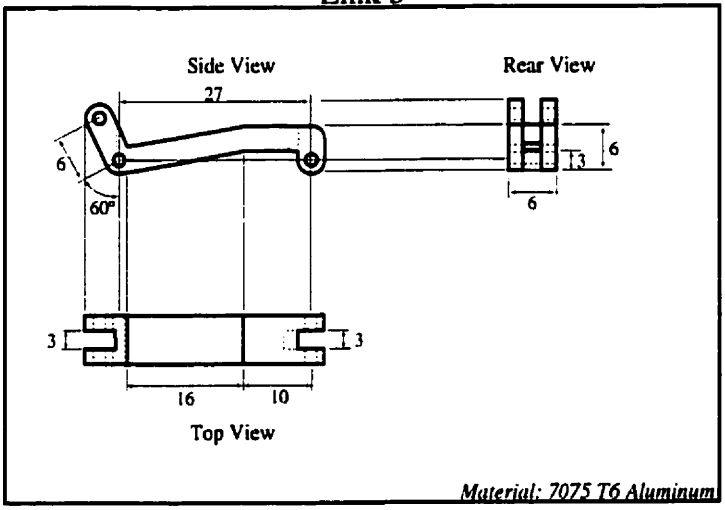
Link 3



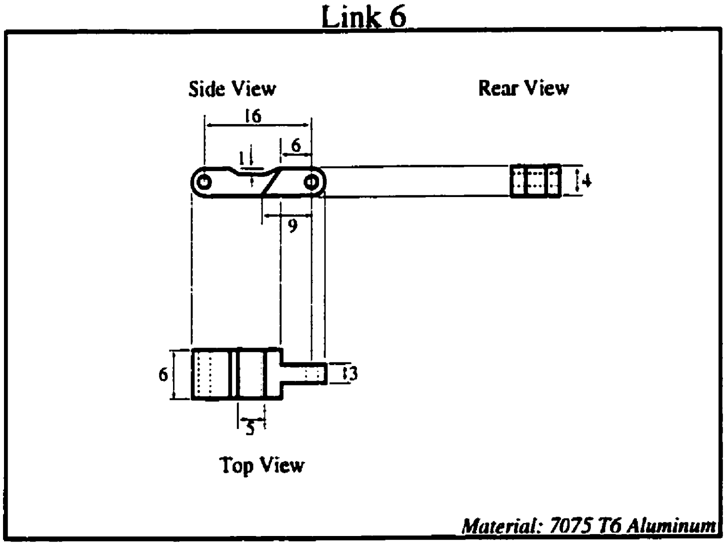
Link 4



Link 5



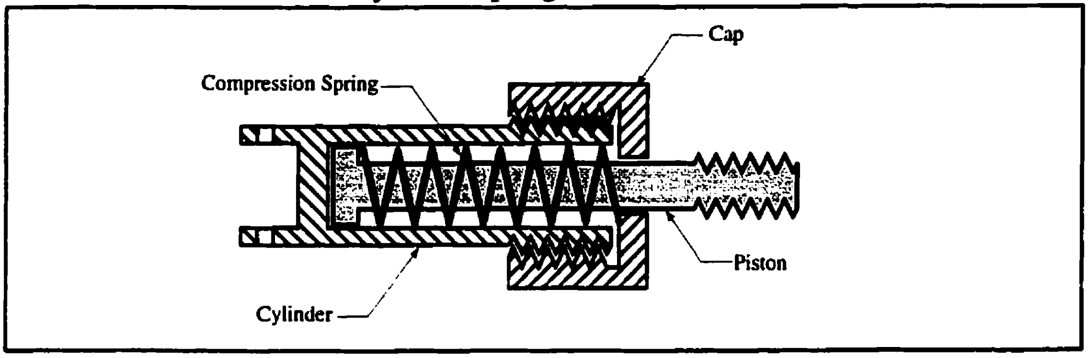
Link 6



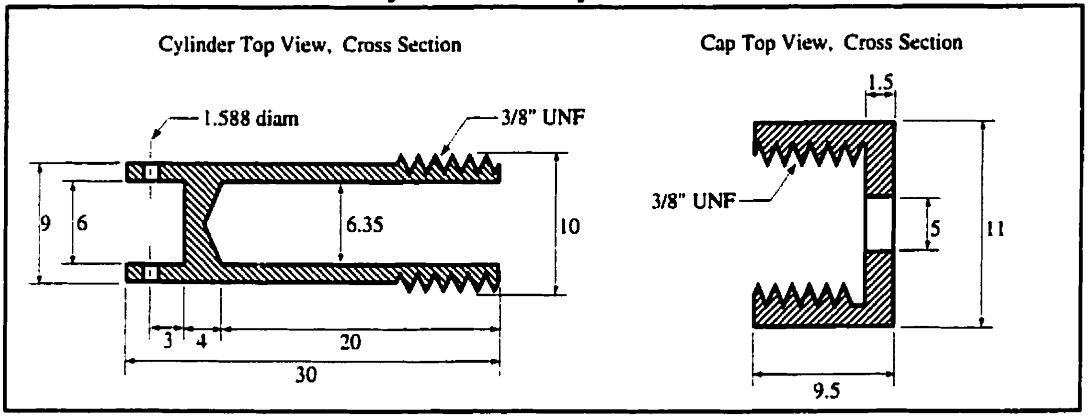
Appendix C.2:

Cylinder Spring Drawings:

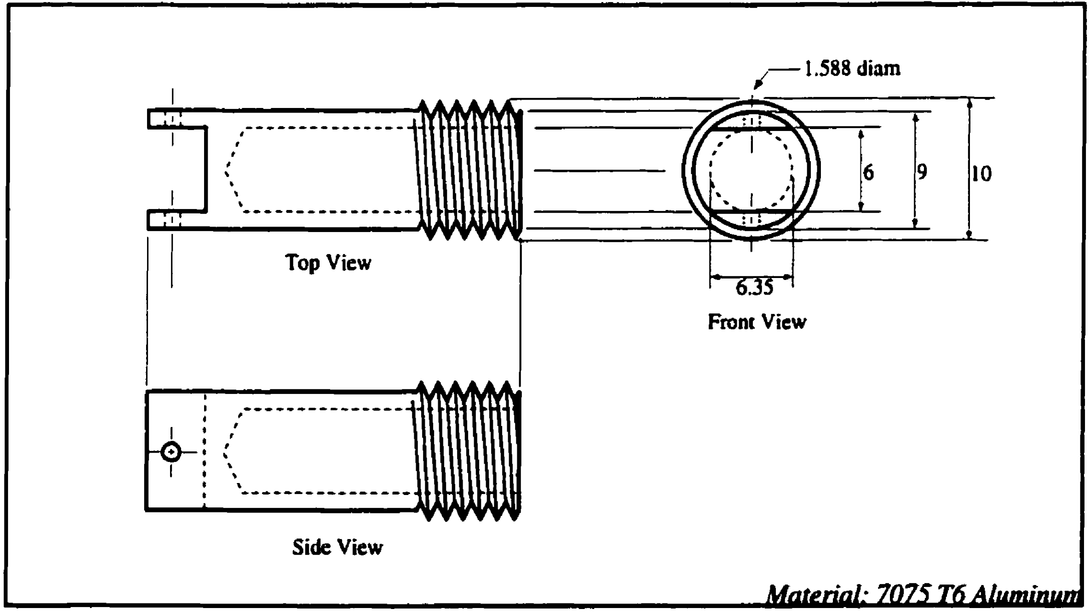
Cylinder Spring Cross Section



Cylinder and Cap Cross Sections

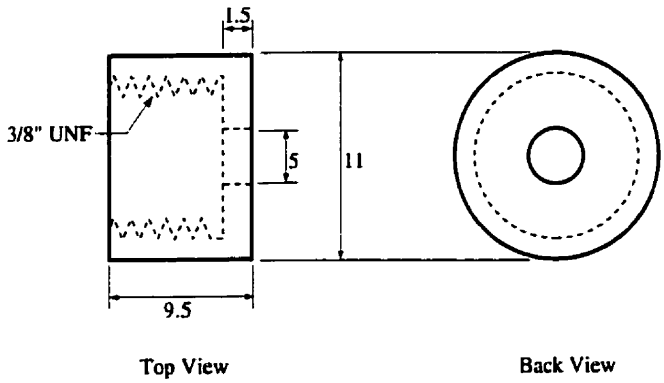


Cylinder



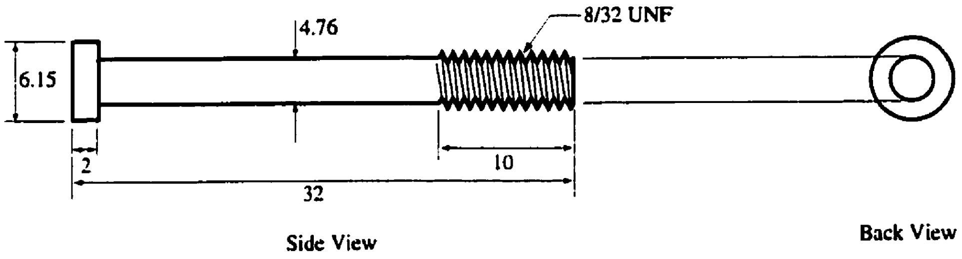
Material: 7075 T6 Aluminum

Cap



Material: 7075 T6 Aluminum

Piston



Material: 7075 T6 Aluminum

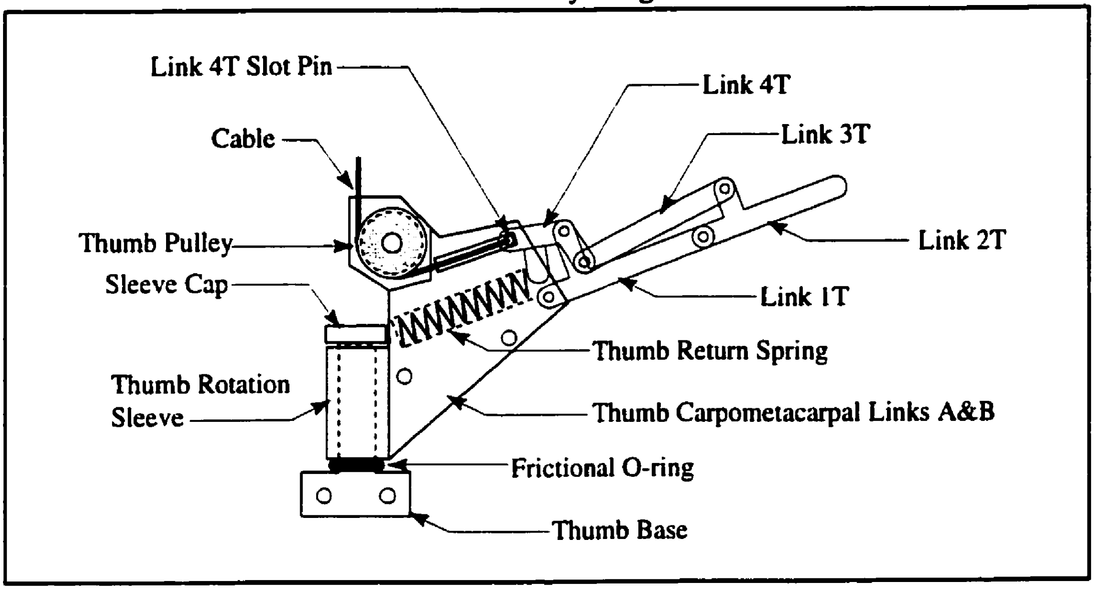
Spring

Uncompressed Length:	*25.4*
Fully compressed Length:	*8.0*
Spring rate (N/mm) :	*1.09*
Outer Diameter:	*6.10*
Wire Diameter:	*0.660*
Inside Diameter:	*4.78*

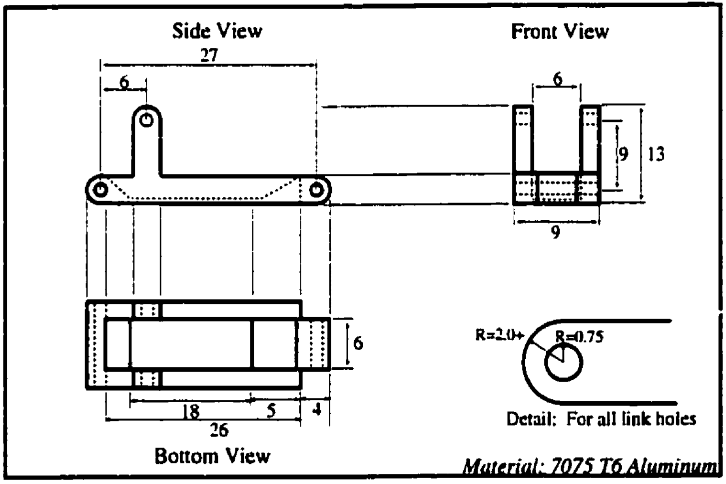
Material: 302 Stainless Steel

Appendix C.3:
Thumb Link Drawings:

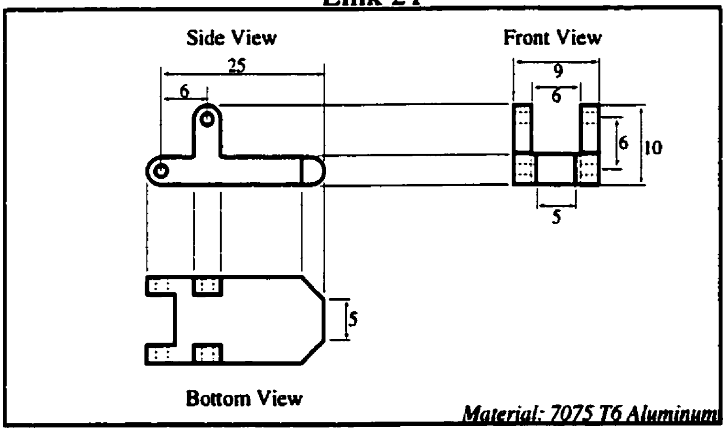
Thumb Assembly Diagram



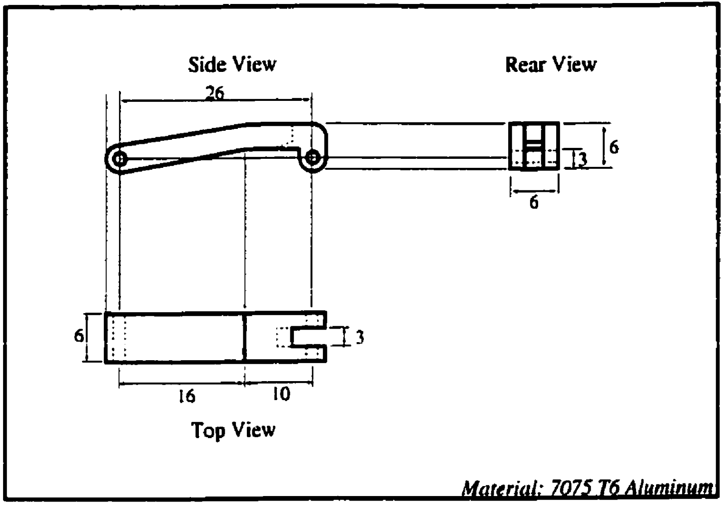
Link 1T



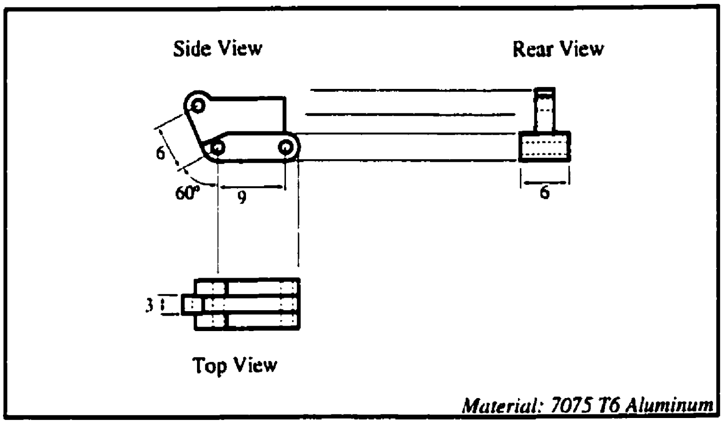
Link 2T



Link 3T



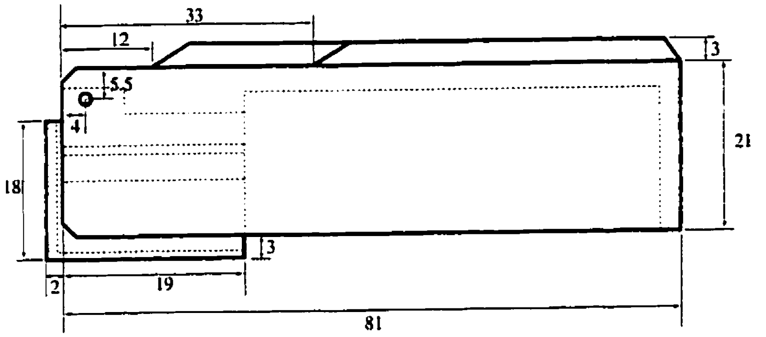
Link 4T



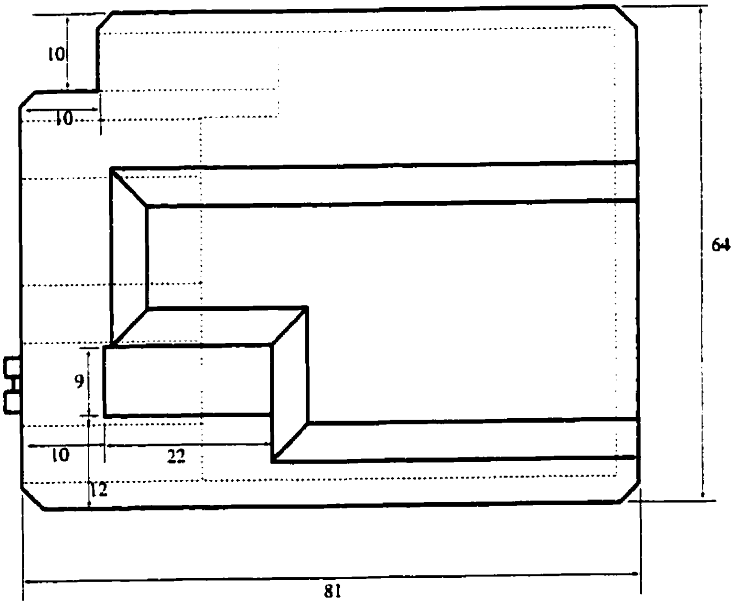
Appendix C.4:
Palm Drawing:

The Palm

Side View



Top View



Material: Delrin plastic

Appendix C.5:

Cost Breakdown for Prototype Hand

NAME:	COST:	
Motor #1724E, 006 V, S, 16AK gearhead, 22:1, 1.4Watts	$131.25	U.S.
Ball Screw, 1mm lead, 6mm O.D. screw, ball diam 0.8mm, efficiency 90%	$235.00	U.S.
Universal Joint, 1/4" O.D., molded Acetal, 27mm long, max Ult Torque 2.5 lbf.	$9.36	U.S.
Springs, 50N @ 10 mm deflection (cost for 10, mass for 2)(302 stainless)	$12.20	U.S.
Springs, 15N @ 10mm deflection, for thumb (cost for 10, mass for 1) (302 stainle	$12.20	U.S.
Cable, 25 Ft, Aramid, 1/32", 50 lbf max tensile, 7/16" pulley	$16.40	CAN
Roll Pins, 1/16" diameter, black oxide steel (40 roll pins needed)	$8.80	CAN
Needle Bearings, 3/16" bore, 1/4" Outer diam, (price for 2)	$24.00	U.S.
Delrin, (1" thick, 12" x 12")	$97.35	CAN
Aluminum Finger links (7075-T6, minimum 3/4" round rod, 12 feet)	$38.00	CAN
Wrist (flat rectangle out of Delrin)	accounted for	
Estimated Machining Costs, at U of T @$35/hour. Estimate 120 hours.	$4,200.00	CAN
Miscellaneous		
stainless 4-40 stove bolts & nuts (10 pairs)	$4.00	CAN
Push on nuts, black oxide steel (5 pairs)	$1.00	CAN
Aquarium Grade Silicone	$1.00	CAN
Materials Total:	$823.77	CAN
*NOTE, exchange rate		
assumed to be at 1.55		
Labour Total:	$4,200.00	CAN
Total Cost:	$5,023.77	CAN

Appendix D:
Motor and Gearbox Selection Calculations:

The 1724E Micro Mo motor has been selected for the prototype hand, using a gearbox with a ratio of 22:1.

When selecting the motor, the primary consideration was the amount of torque available at a given speed. When this torque is subsequently geared through the gearbox and transferred into linear motion via the ball screw, certain amount of force is expected.

A list of components selected along with some of their specifications, is shown below:

1) Miniature lead screw and ball nut assembly. Part #(MRB 0601)
   Efficiency of converting torque into linear load quoted as greater than 90%.
   (NOTE: this has been quoted by three different sources, for ball/screw assemblies)
   Load Rating: 58 kg Dynamic, 120 kg Static.
   (The prototype hand will operate on an intermittent duty cycle, at low speed, therefore it is assumed that the static load rating is more applicable)
   Lead: 1mm
   Diameter: 6mm
   Weight: 59 grams for a screw 8" long and the ball nut.
   (Only 2" of screw is needed for the prototype hand, therefore half the weight given above would be 29 grams)
   Cost: $235 U.S. (This is most expensive part).

2) Motor Part #(1724E)

Supply Voltage:	6 V
Armature Resistance:	4 ohms
Maximum Power:	2.25 Watts (1.92 watts max anticipated for our use,during pinch) (0.914 watts minimum during empty close)
Stall Torque:	1.49 oz-in
Torque Constant:	1.00 oz-in/Amp
Weight:	26 grams

3) Gearbox Part #(16AK)

Efficiency:	73%
Gear Ratio:	22:1
Maximum Output Torque:	14.2 oz-in (intermittent use)
Weight:	4 grams

Analysis:

The force that is currently desired is approximately 600 N on the ball nut attached to the lead screw. The lead screw must translate the ball nut at approximately 5 mm/sec, through a distance of 14 mm. Motor speed is effected by the load on the motor, therefore this load must be estimated. During closure, the hand will need to overcome only the frictional forces. These include friction in the finger links, the slot pins, adaptive springs, roller bearings, glove, lead screw and gearbox.

The following forces must be overcome:

Finger Links:

The total frictional force is only a guess. It is hoped that each digit will have no more than 5 N in frictional losses during an open or close.

Adaptive Grasp Springs:

Are not active during an open or empty close and transmit all force. Therefore, there should be no losses.

Roller Bearings:

This is a guess. Assume total of 15 N frictional loss for both roller bearings.

Thumb Return Spring:

Because the thumb is attached via a cable, the thumb needs a return spring to 'pull' it back into the open position. The thumb friction is anticipated to be 5 N and the sliding friction for the cable about the two smaller pulleys could be about 5 N as well. Therefore, a return spring capable of 15 N of force should be sufficient. This 15 N spring will probably have a minimum threshold force of 3 N before deflection begins, therefore the force of the spring will vary between 3 N (thumb open) to 15 N (thumb closed). An average resistive force of 12 N will be assumed for the purposes of the motor load estimate.

(*NOTE* the fingers do not need return springs because it is assumed that the Cylinder Spring mechanisms will be able to carry the reverse opening load of 10 - 20 N.)

The Glove:

There is currently no glove as part of this design, however a reasonable allowance for glove friction must be incorporated. A conventional glove cannot be used with this hand. A conventional glove simply was not made for a hand with flexible, adaptive digits. A new glove must be designed for this hand which is durable and yet flexible at joint locations. Assume that a requirement for a future glove design would be that the total resistive frictional force of the glove would be no more than 25 N.

Therefore, the total frictional force is estimated at about 77 N.
***(The original estimate was based on the design with the equaliser mechanism, which was assumed to have a frictional force of 25 N. Therefore, the total estimate used in the subsequent calculations is 77 N + 25 N = 102N)

Therefore, the hand must overcome a load of 102 N while it is closing empty. It must also translate the ball screw at approximately 5 mm/sec, so that it can achieve the pinch position in approximately 1 second(from the full open position).

102 N is the force that the ball nut will experience during an empty close.

The equation for converting lead screw torque to ball nut force is supplied by the manufacturer of the assembly as follows:

Torque (lbf-in) = (0.177)*[load (lbf)]*[lead (in)]

102 N is equal to 23.0 lbf (this is the load)
1mm lead is equal to 0.03937 in

Therefore the required torque on the lead screw to overcome our frictional load is :

$$\begin{aligned}\text{Torque(lbf-in)} &= (0.177)*(23.0)*(0.03937)\\ &= 0.160 \text{ lbf-in.}\end{aligned}$$

The lead screw is 90% efficient at converting torque into linear load.

Therefore $(0.160/.90) = 0.178$ lbf-in of torque is actually needed at the motor end.

0.178 lbf-in of torque is equal to 2.85 oz-in of torque.

A Micro Mo 16AK 22:1 gearbox is used, which is 73% efficient at transmitting torque.

Therefore the torque is multiplied 22 times and transmission loss is accounted for at 73%.
$=(2.85/22)/0.73$

$=0.178$ oz-in that the motor must overcome.

Next, the speed at which the motor operates when it is loaded with 0.178 oz-in of torque, must be determined.

The motor manufacturer (Micro Mo) has supplied the following equation:
*(NOTE: this equation was also independently confirmed by using an electric machines engineering text)

$$w = (Vo/Ke) - (Tl * Rm) / (Kt * Ke)$$

where:

w = speed (rpm)
Vo = supply voltage (V) $= 6$
Ke = Back Emf constant (V/rpm) $= 0.000743$
Tl = Torque load (oz-in) $= 0.178$
Rm = armature resistance(ohms) $= 4$
Kt = Torque constant (oz-in/Amp) $= 1.00$

Therefore:

$$w = (6/0.000743) - (0.178*4)/(1.00*0.000743)$$

$$w = 7117 \text{ rpm}$$

7117 rpm is equal to 118 rev/sec.

This speed is geared down through the gearbox 22 times, so that:

the lead screw turns at 5.39 rev/sec.

Since the lead of the lead screw is 1mm, this means that:

The ball nut will translate at 5.39 mm/sec.

Total pinch force:

When talking to Isaac Kurtz(28) from the electronics laboratory, motor selection was discussed at great length along with the possible electronics that could drive the motor.

Isaac mentioned that it was easy to use the conventional VASI hand motor controller (which drives a 1624 motor) since it is capable (when modified slightly) to supply 1 to 1.2 amps of current before it goes into energy saving mode.

Therefore, it was decided to use this motor controller with a shut off at 1 amp.

The Torque constant for the 1724 motor is 1.00 oz-in/Amp

Therefore, 1.00 oz-in of torque is developed when 1 amp is applied.

The motor speed at this torque is approximately 2600 rpm (calculation not shown). However, speed is not important after the hand has achieved the final grasp position. Only torque is of interest.

When the maximum output torque of the motor is geared up 22 times and the efficiency of 0.73% for the gearbox is taken into account, the output torque is:

torque = (1.00 oz-in) * 22 * 0.73
torque = 16.06 oz-in

This is the torque that is applied to the lead screw.

Using the lead screw equation to convert torque into linear load:

Torque (lbf-in) = (0.177)*[load (lbf)]*[lead (in)]

16.06 oz-in is equal to 1.0038 lbf-in (This is the torque)
1mm lead is equal to 0.03937 in

Therefore the load developed is 144.04 lbf. Since the lead screw is only 90% efficient:

The load available at the ball nut is 129.64 lbf

129.64 lbf is equal to 575 N

102 N are considered to be lost, therefore:

475 N are available for pinch purposes.

In previous analysis using the Working Model software, it has been observed that with 500 N of force available, a tri-digital pinch force of 27 N (6.1 lbf) at the tips can be realised.

Depending upon the configuration of the grasp, up to 15 mm of distance must be covered by the ball nut. Only 5 mm of translation is needed to close to a pinch position, with no force developed.

Appendix D.1:
Revised Motor & Working Model Calculations:

The motor controller is set with a maximum cut-off current of 1.1 amp.

The torque constant for the 1724E motor is 1.00 oz-in/Amp

Therefore, 1.10 oz-in of torque is developed at the motor.

When this motor torque is geared up 22 times and the efficiency of 0.73% for the gearbox is taken into account, the output torque is:

torque = (1.10 oz-in) * 22 * 0.73

torque = 17.66 oz-in   This is the torque leaving the gearbox.

Assume a 90% efficiency through the U-joint (or straight shaft) to the lead screw:

Therefore, 15.90 oz-in of torque is available at the lead screw.

The lead screw equation is used to convert torque into linear load,
*Note, the equation incorporates the 90% efficiency of the ball screw:

Torque (lbf-in)   =   (0.177)*[load (lbf)]*[lead (in)]

15.90 oz-in is equal to 0.9937 lbf-in   (This is the torque)
1mm lead is equal to 0.03937 in

Therefore the load available at the ball screw is: 142.60 lbf

142.60 lbf is equal to 634N

102 N are considered to be lost, therefore:

534 N are available for pinch purposes.

In revised analysis using the Working Model software, it has been observed that with 500 N of force available, a tri-digital pinch force of 36 N (8.1 lbf) at the tips can be realised.

NOTE: Re-analysis after experiment.

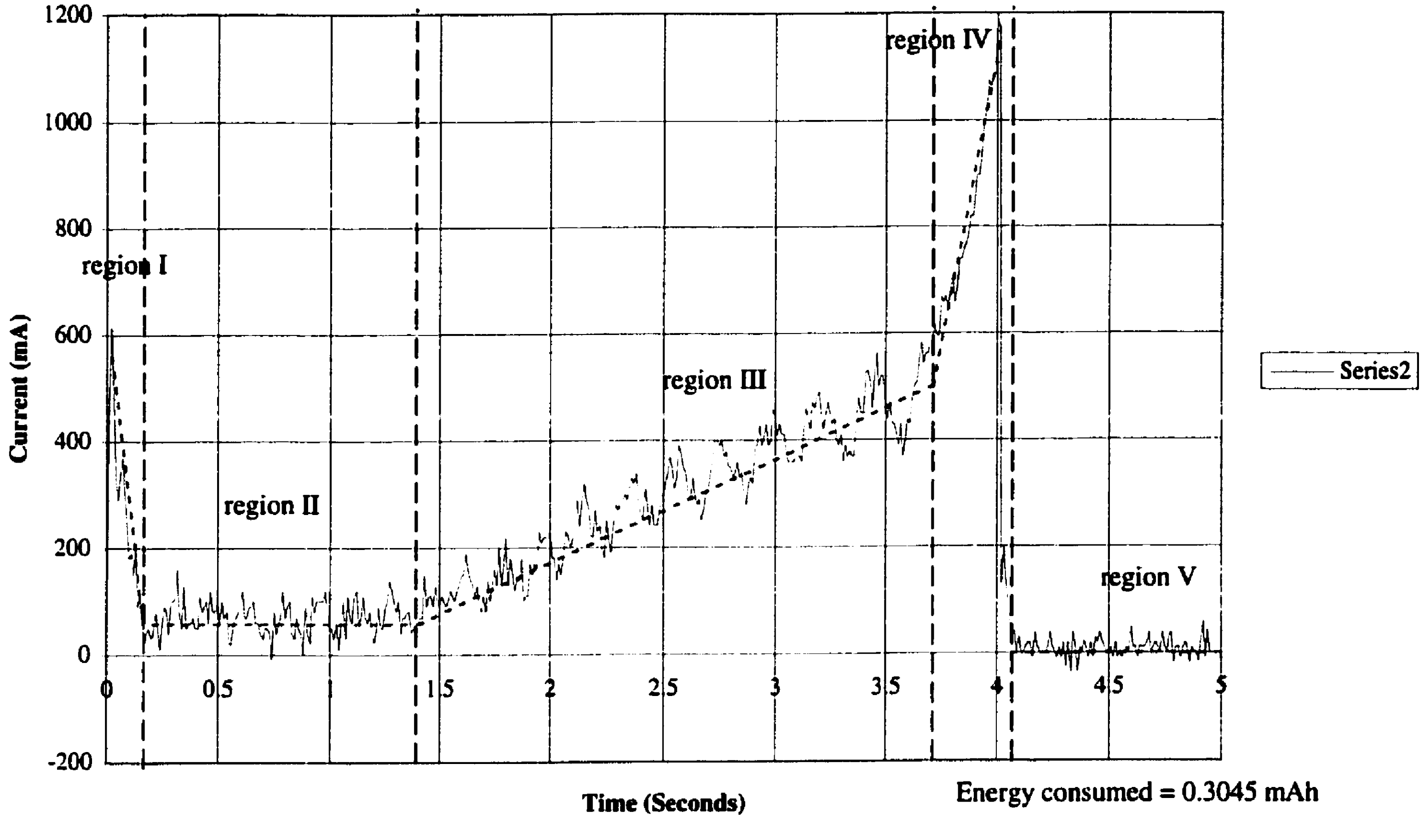
The test results reveal that 9.36 oz-in of torque applied at the ball screw are used solely to overcome combined mechanism and Cylinder Spring resistance.

This leaves (15.90 - 9.36) = 6.54 oz-in of torque available to develop the pinch force.

This torque can only create 261 N of load available at the ball screw, to be used for pinch.
261 N of load can only create a theoretical maximum of 18.7 N (4.2 lbf) of pinch.

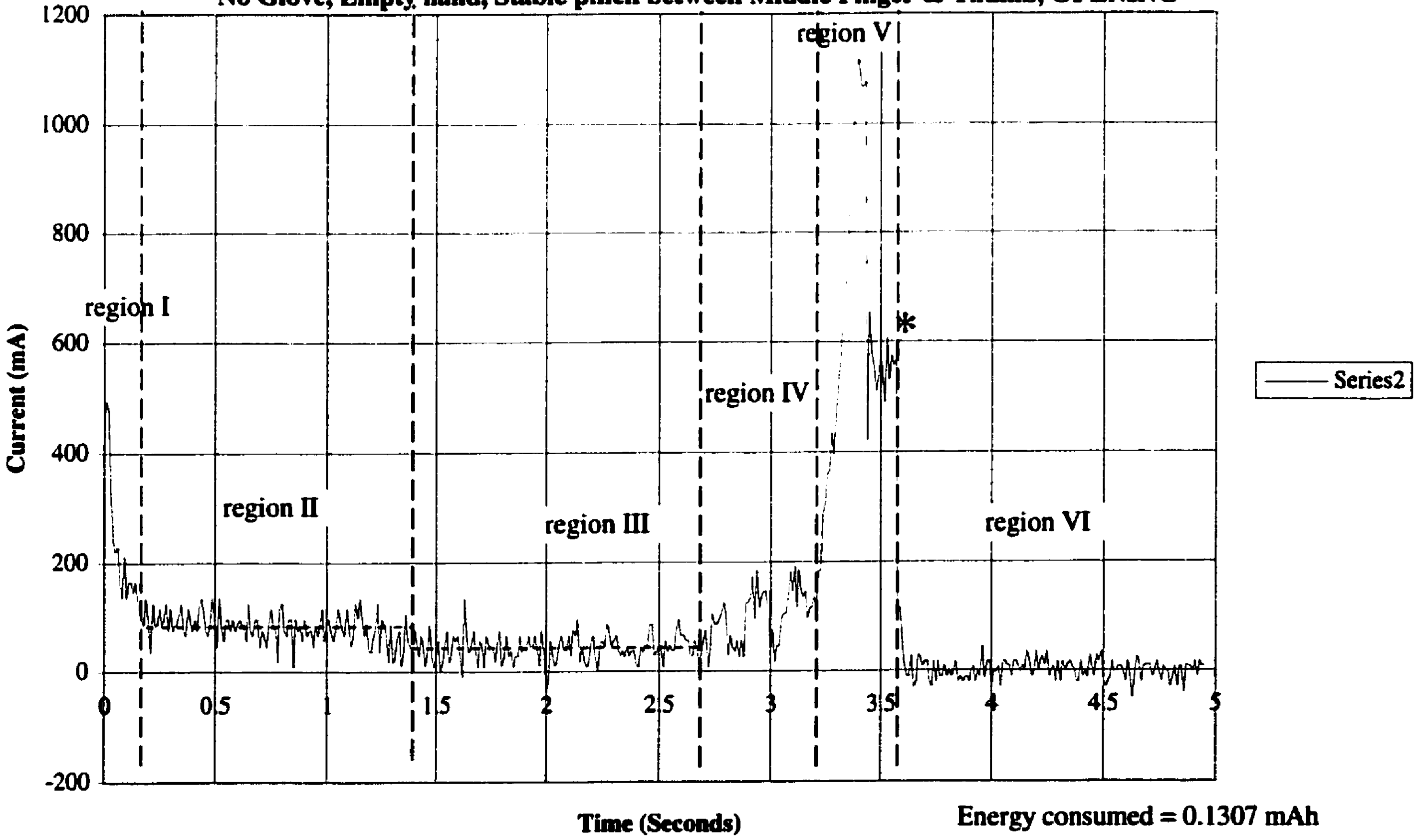
Appendix E:
Current and Energy Consumption Graphs:

GRAPH E1 (Prototype Hand)
Motor Current vs. Time (Averaged)
No Glove, Empty hand, Stable pinch between Middle Finger & Thumb, CLOSING

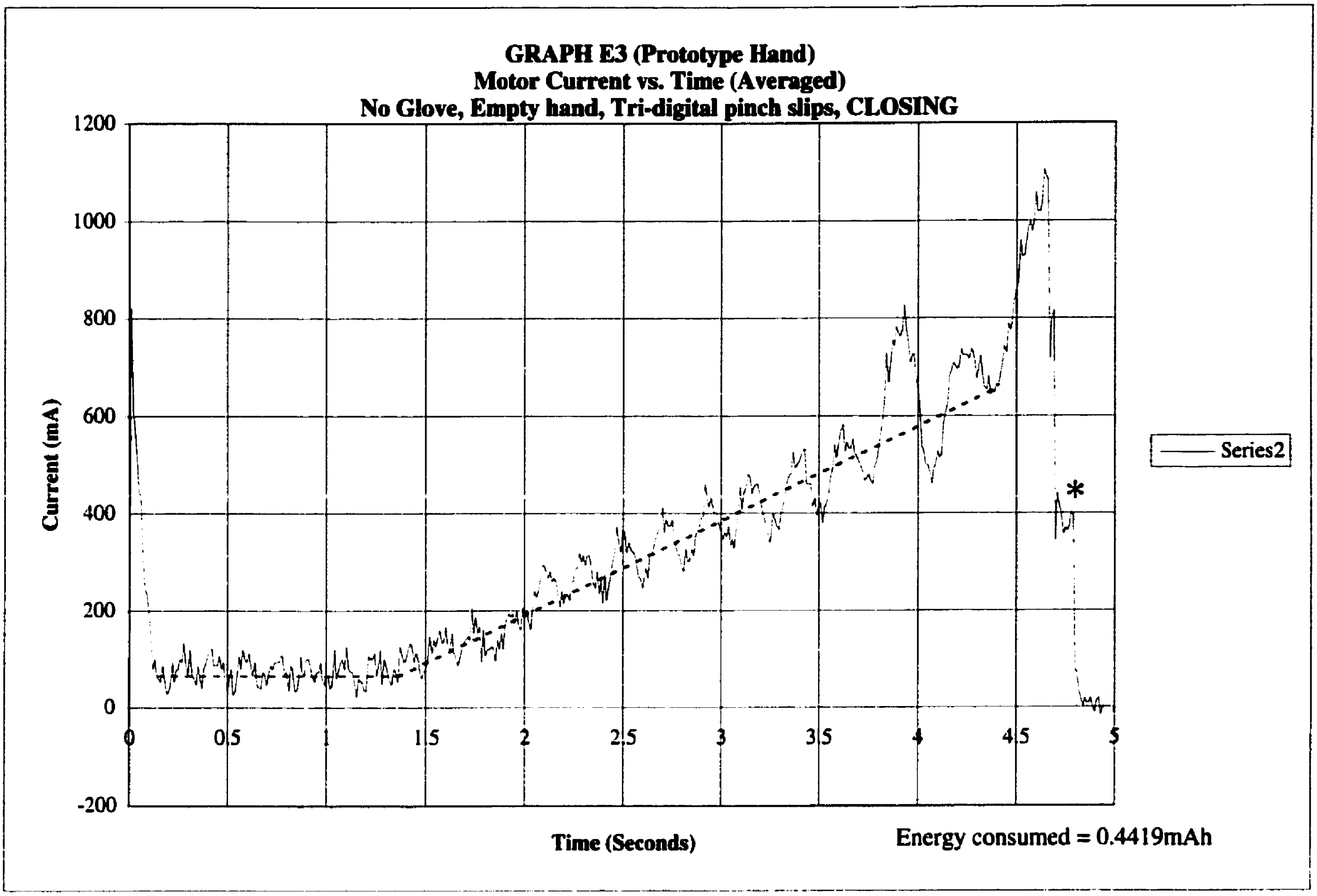


Energy consumed = 0.3045 mAh

GRAPH E2 (Prototype Hand)
Motor Current vs. Time (Averaged)
No Glove, Empty hand, Stable pinch between Middle Finger & Thumb, OPENING

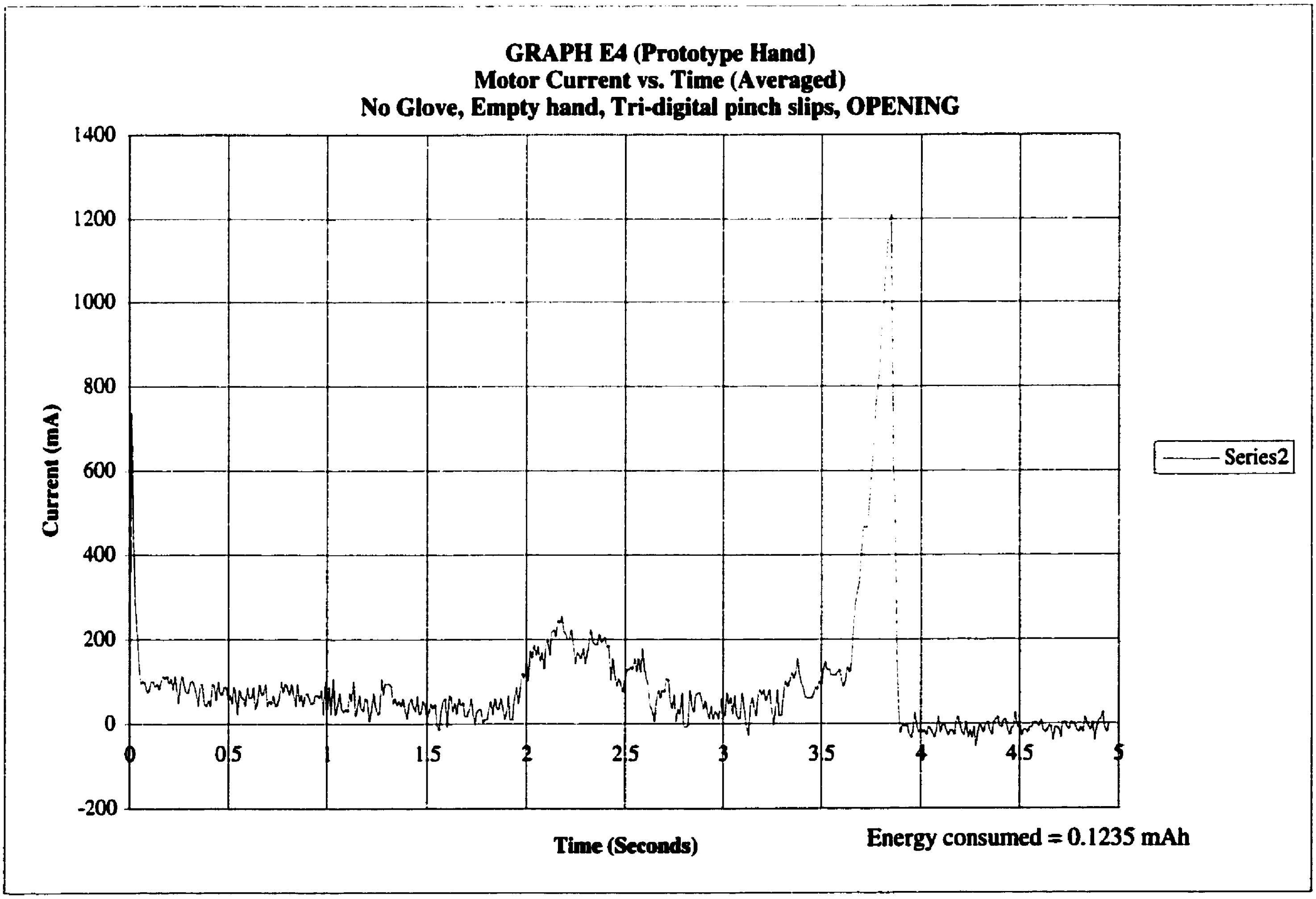


Energy consumed = 0.1307 mAh



GRAPH E3 (Prototype Hand)
Motor Current vs. Time (Averaged)
No Glove, Empty hand, Tri-digital pinch slips, CLOSING

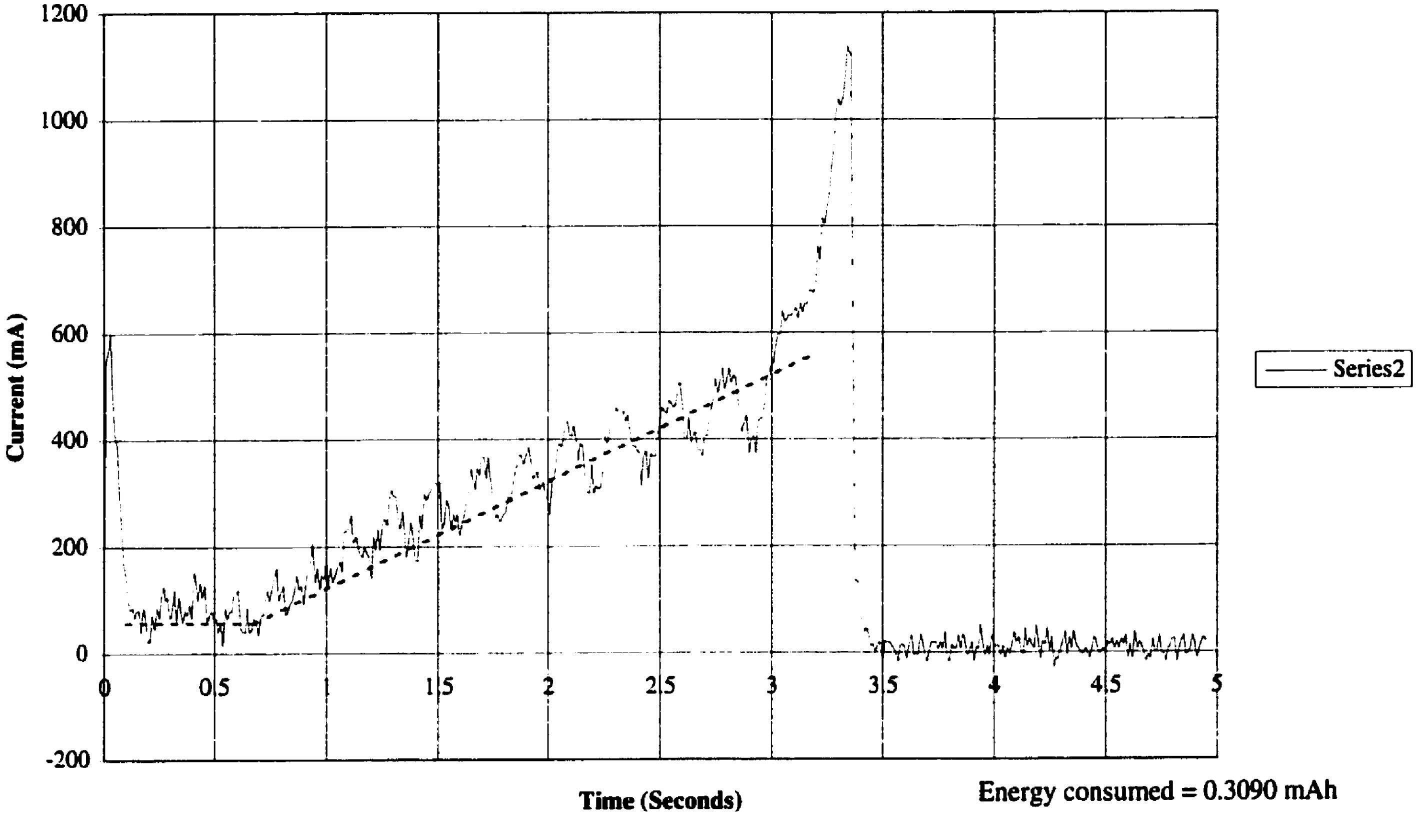
Energy consumed = 0.4419mAh



GRAPH E4 (Prototype Hand)
Motor Current vs. Time (Averaged)
No Glove, Empty hand, Tri-digital pinch slips, OPENING

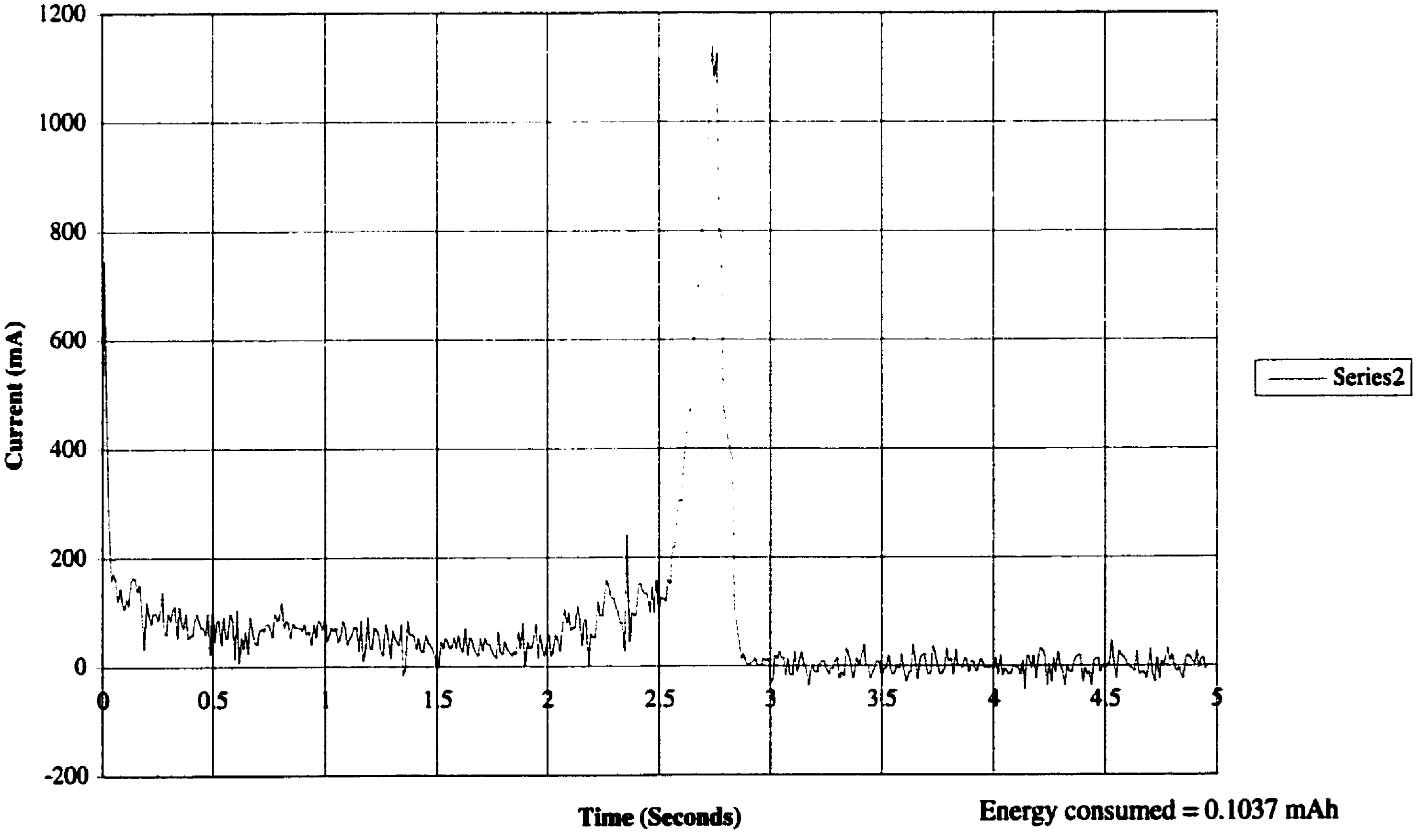
Energy consumed = 0.1235 mAh

GRAPH E5 (Prototype Hand)
Motor Current vs. Time (Averaged)
No Glove, 51.1mm diam cylinder, CLOSING



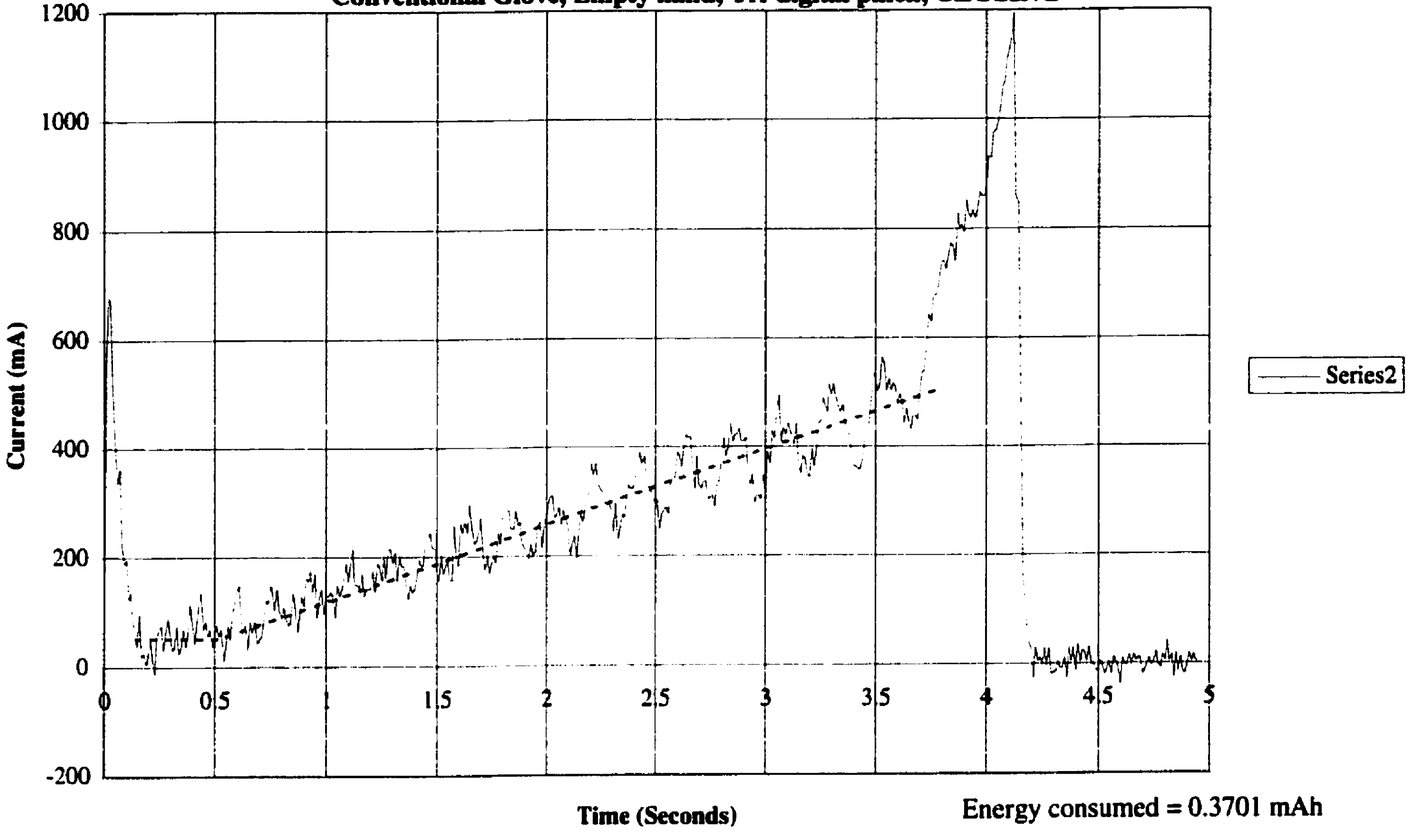
Energy consumed = 0.3090 mAh

GRAPH E6 (Prototype Hand)
Motor Current vs. Time (Averaged)
No Glove, 51.1mm diam cylinder, OPENING



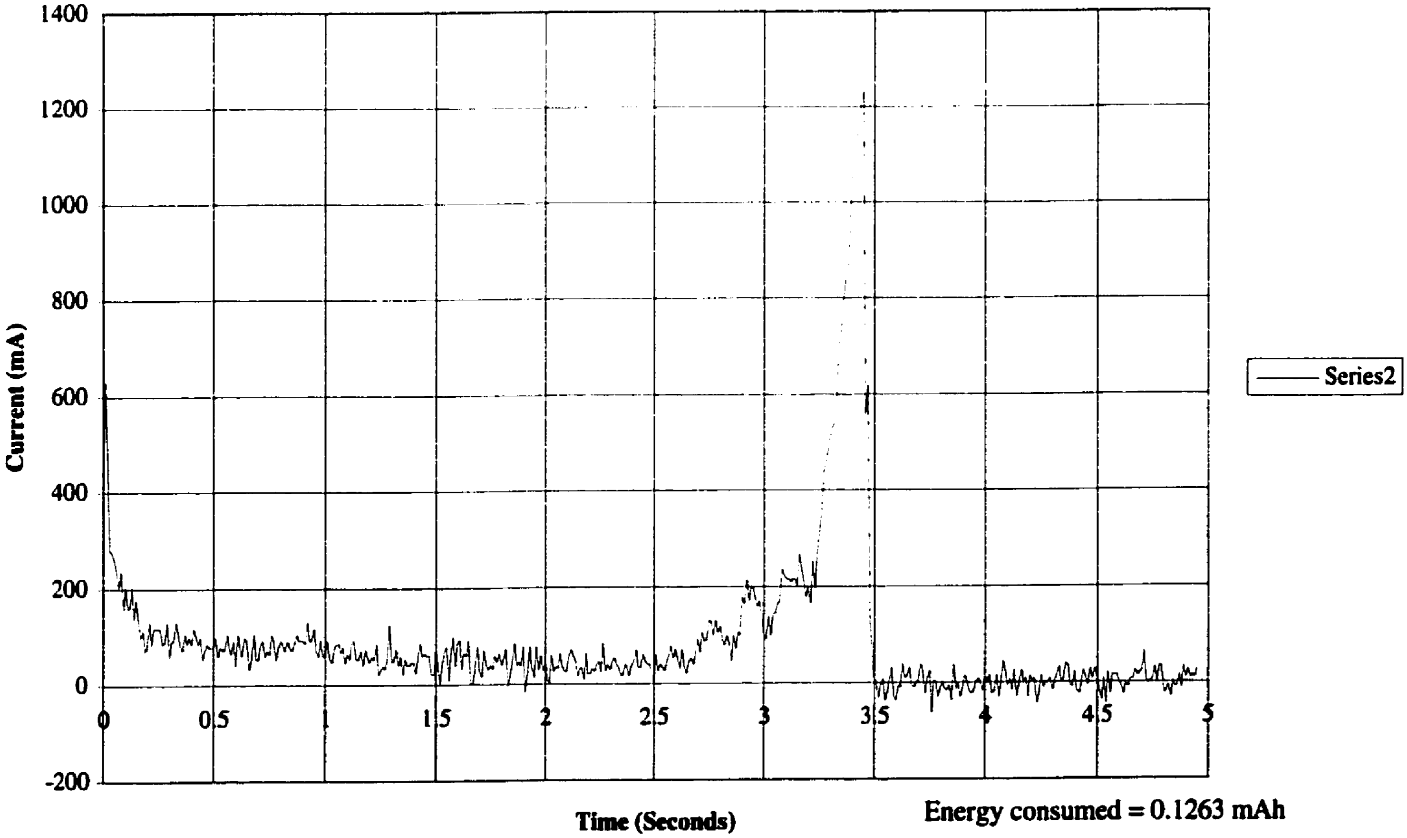
Energy consumed = 0.1037 mAh

GRAPH E7 (Prototype Hand)
Motor Current vs. Time (Averaged)
Conventional Glove, Empty hand, Tri-digital pinch, CLOSING



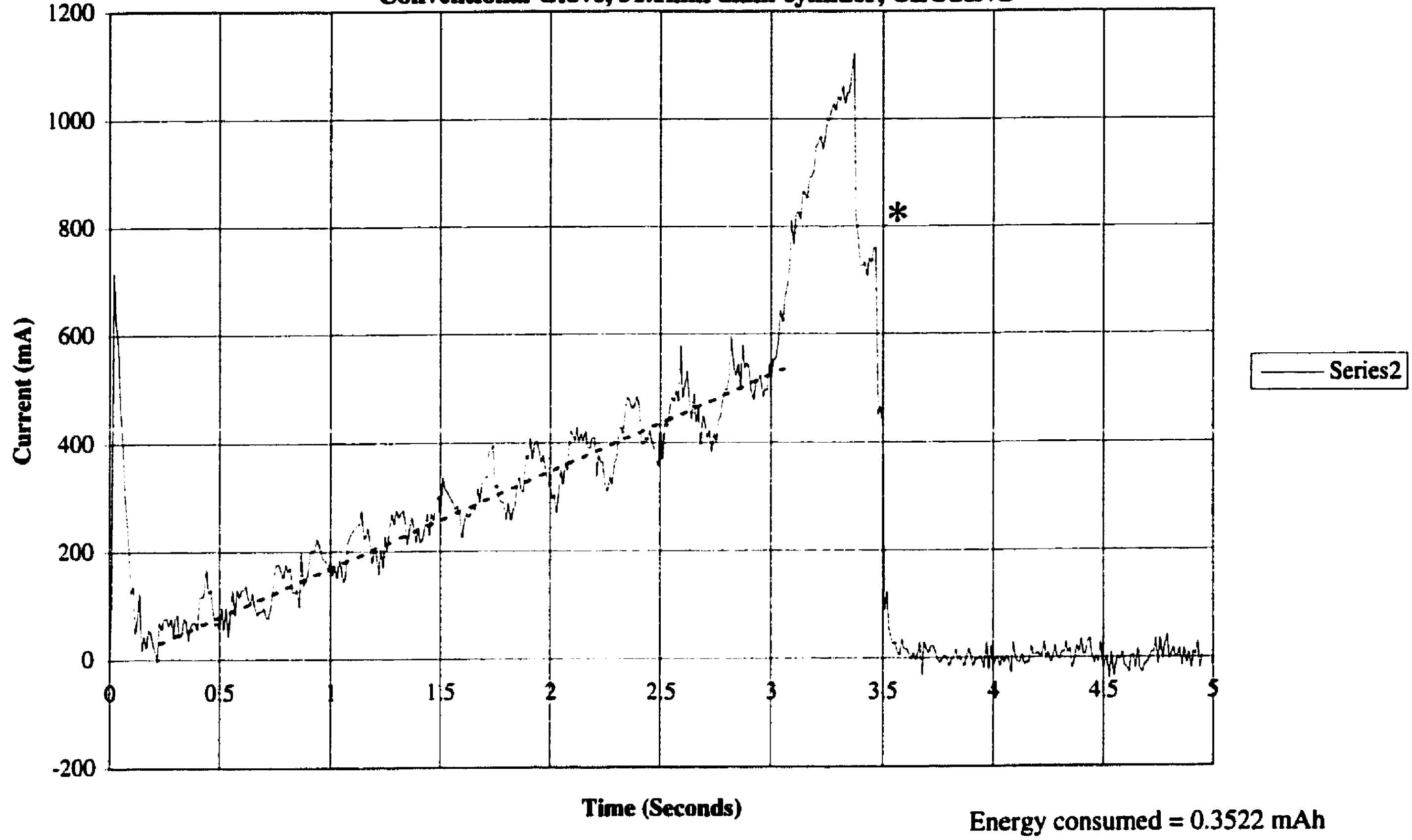
Energy consumed = 0.3701 mAh

GRAPH E8 (Prototype Hand)
Motor Current vs. Time (Averaged)
Conventional Glove, Empty hand, Tri-digital pinch, OPENING



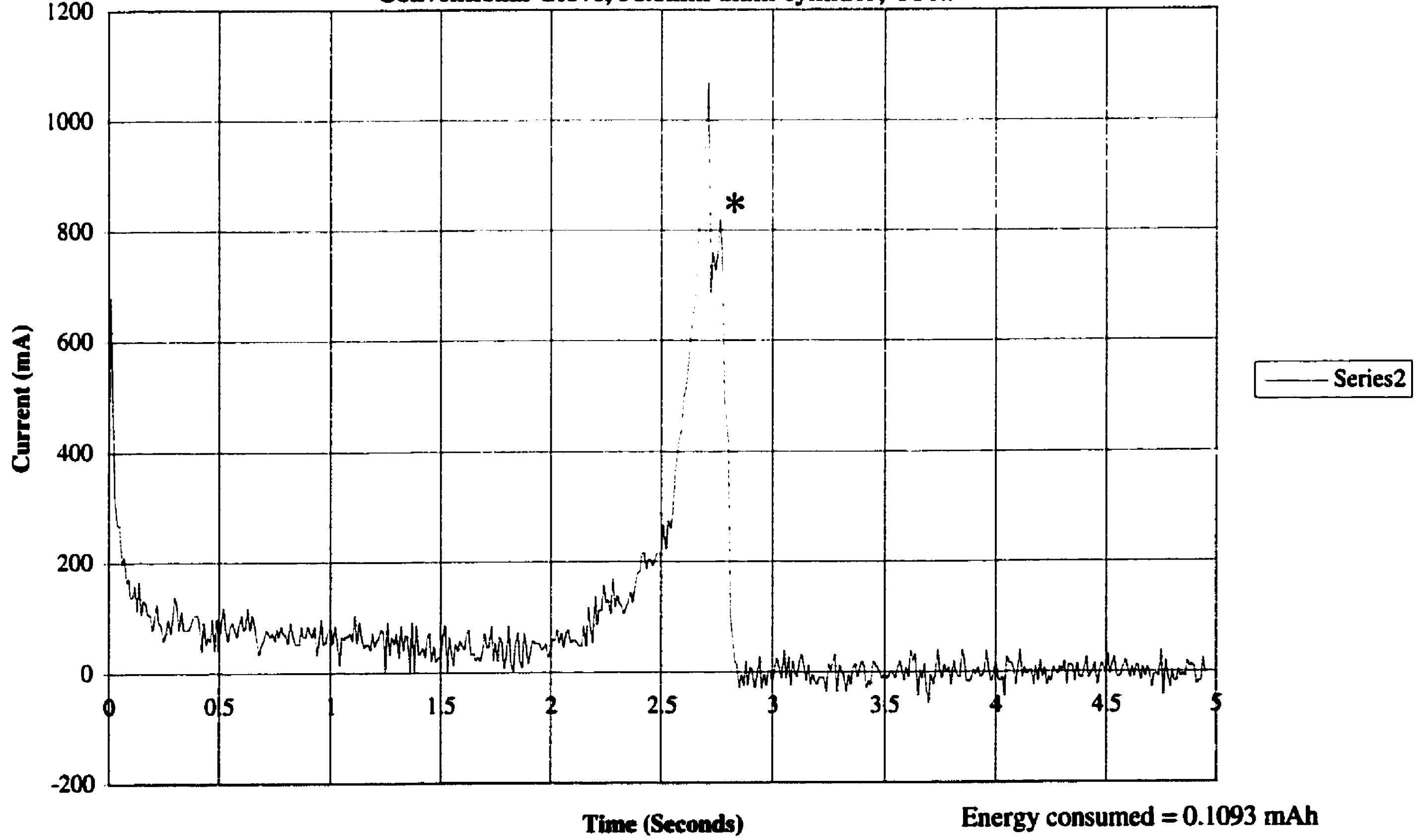
Energy consumed = 0.1263 mAh

GRAPH E9 (Prototype Hand)
Motor Current vs. Time (Averaged)
Conventional Glove, 51.1mm diam cylinder, CLOSING



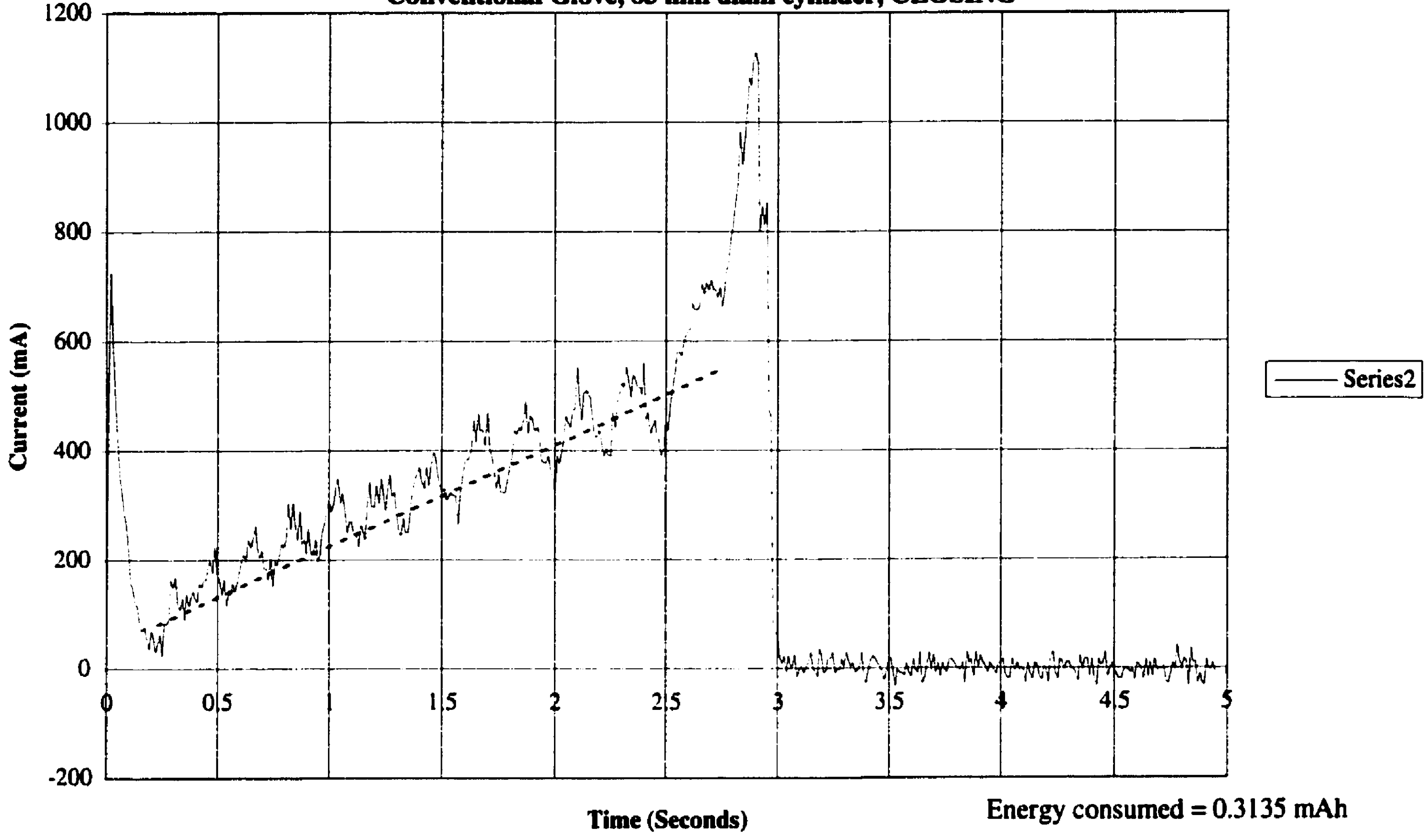
Energy consumed = 0.3522 mAh

GRAPH E10 (Prototype Hand)
Motor Current vs. Time (Averaged)
Conventional Glove, 51.1mm diam cylinder, OPENING



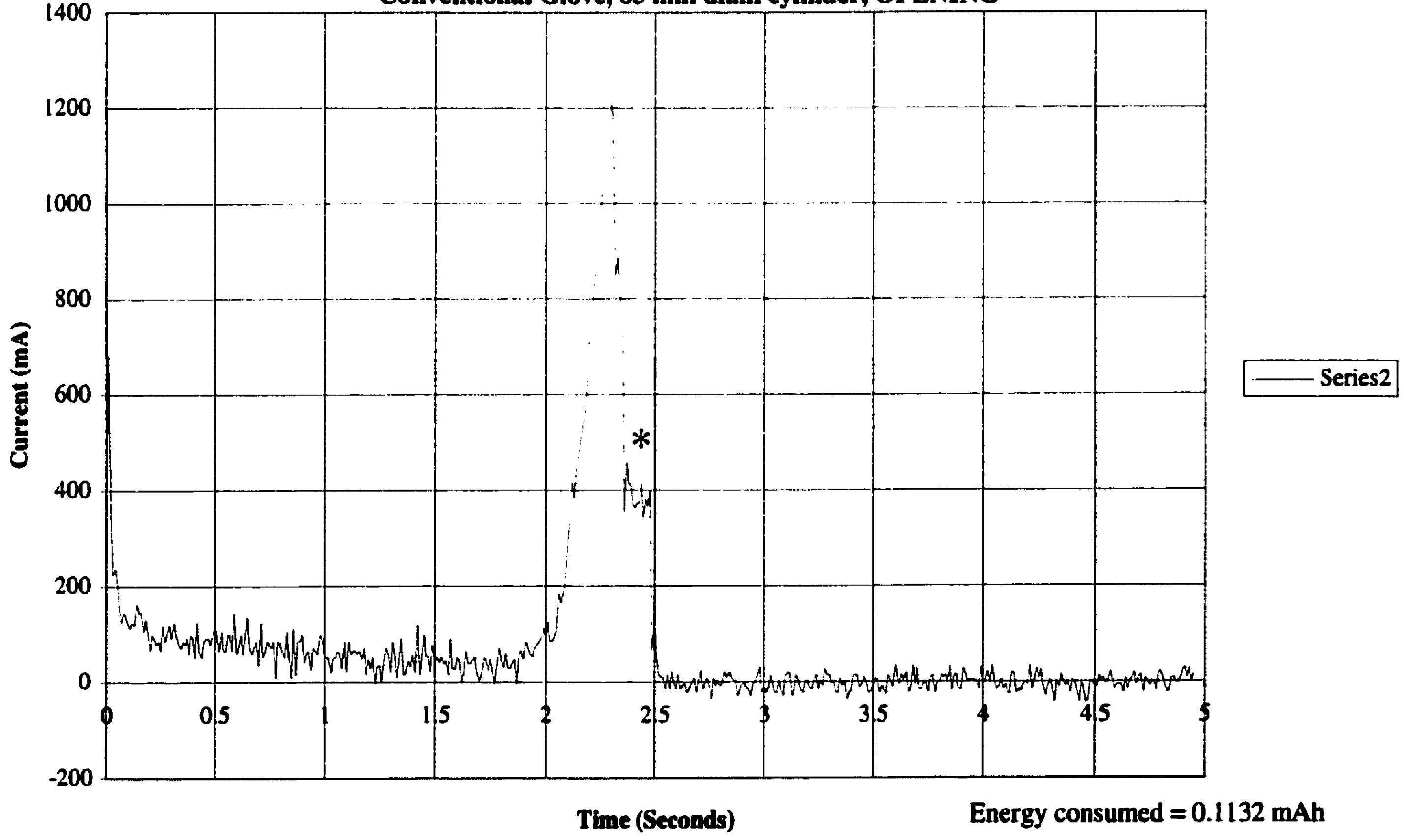
Energy consumed = 0.1093 mAh

GRAPH E11 (Prototype Hand)
Motor Current vs. Time (Averaged)
Conventional Glove, 83 mm diam cylinder, CLOSING



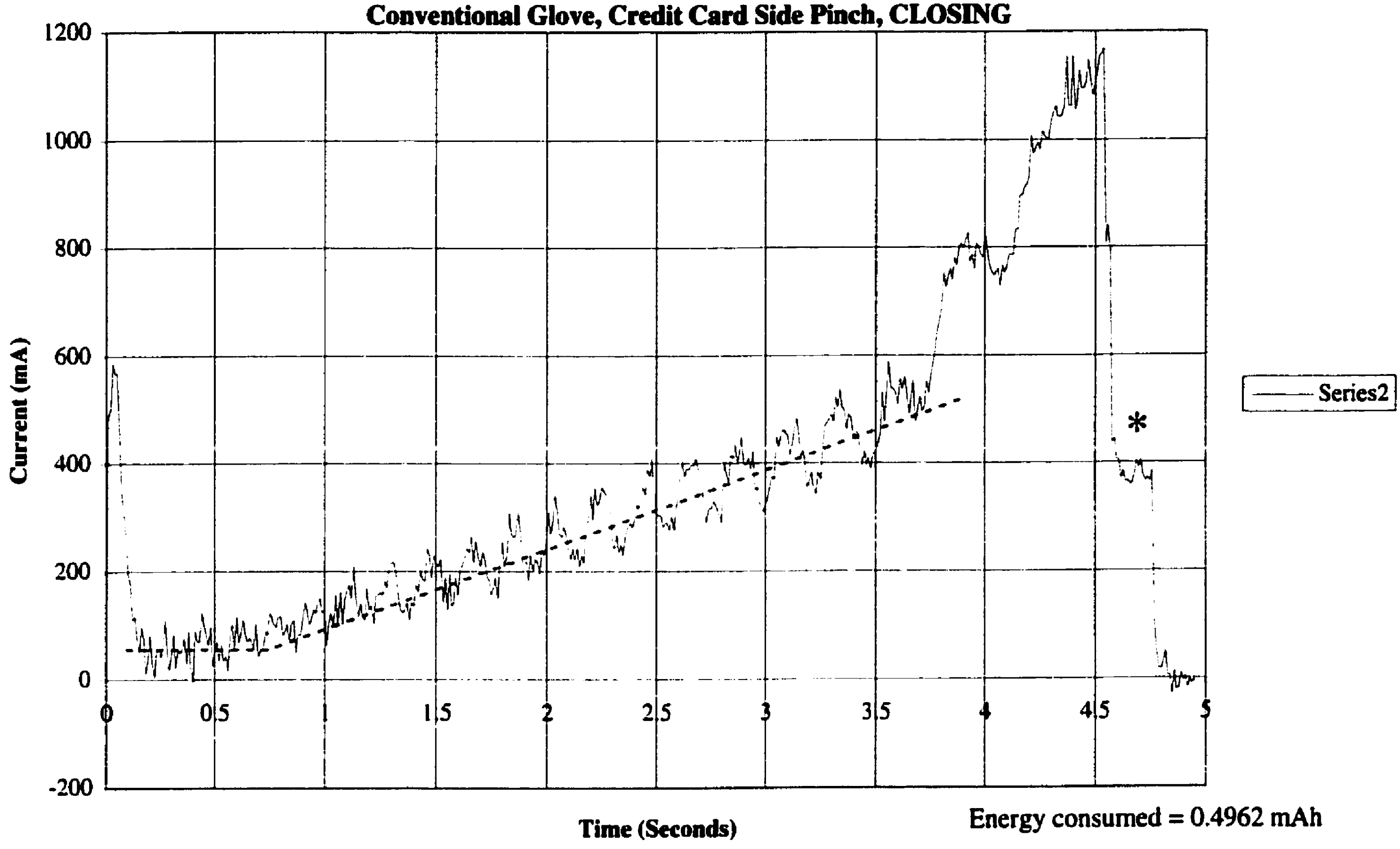
Energy consumed = 0.3135 mAh

GRAPH E12 (Prototype Hand)
Motor Current vs. Time (Averaged)
Conventional Glove, 83 mm diam cylinder, OPENING



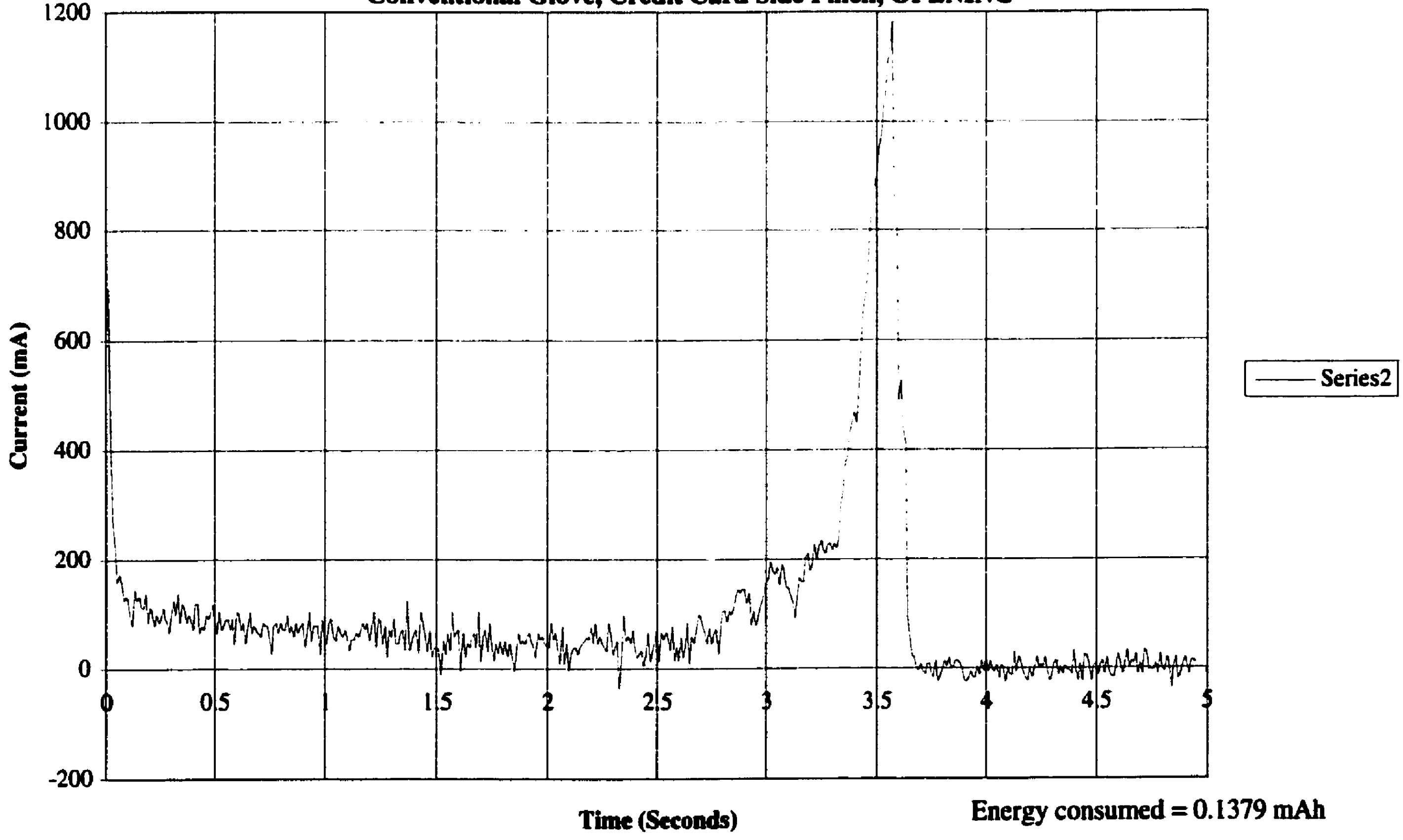
Energy consumed = 0.1132 mAh

GRAPH E13 (Prototype Hand)
Motor Current vs. Time (Averaged)
Conventional Glove, Credit Card Side Pinch, CLOSING



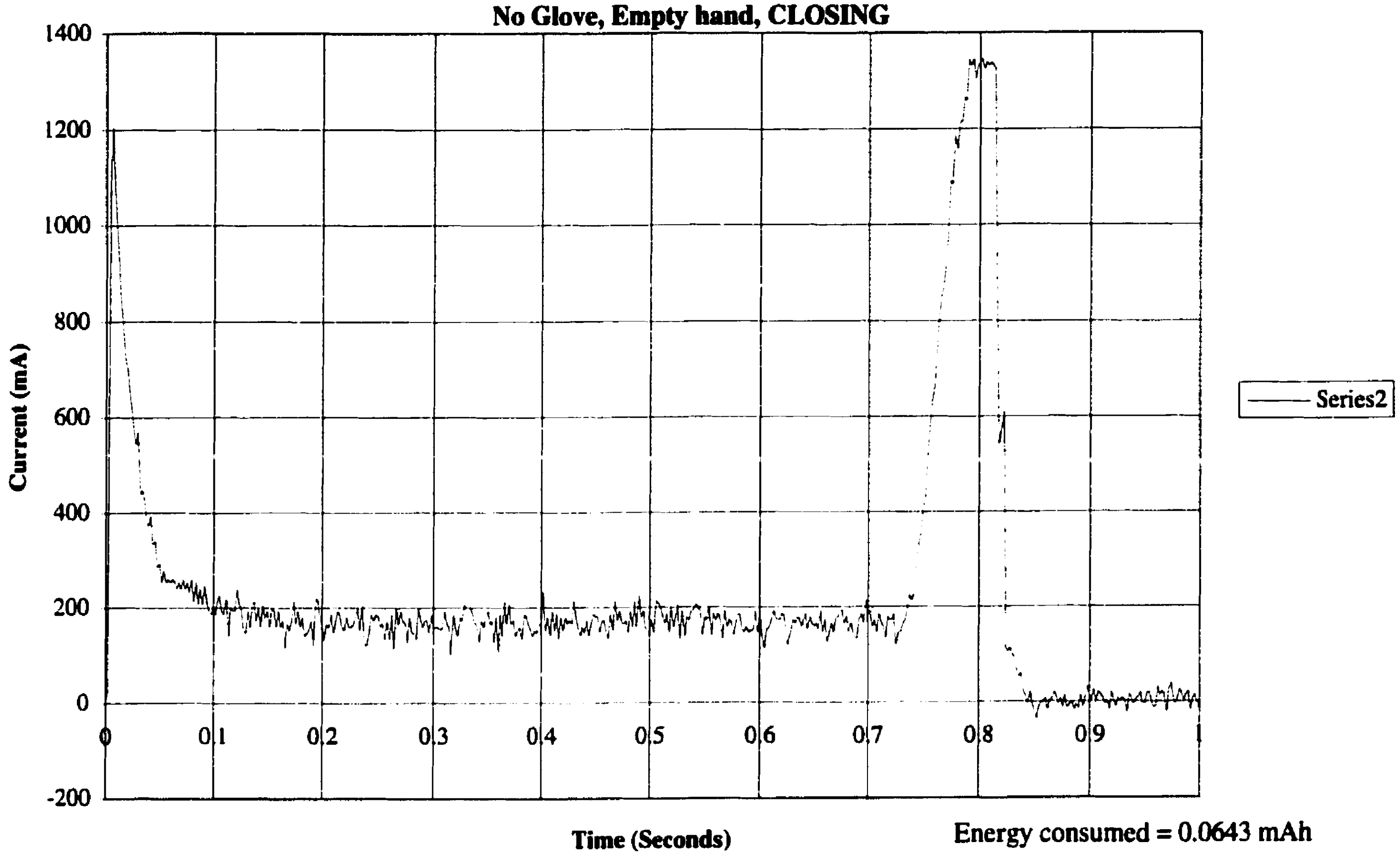
Energy consumed = 0.4962 mAh

GRAPH E14 (Prototype Hand)
Motor Current vs. Time (Averaged)
Conventional Glove, Credit Card Side Pinch, OPENING



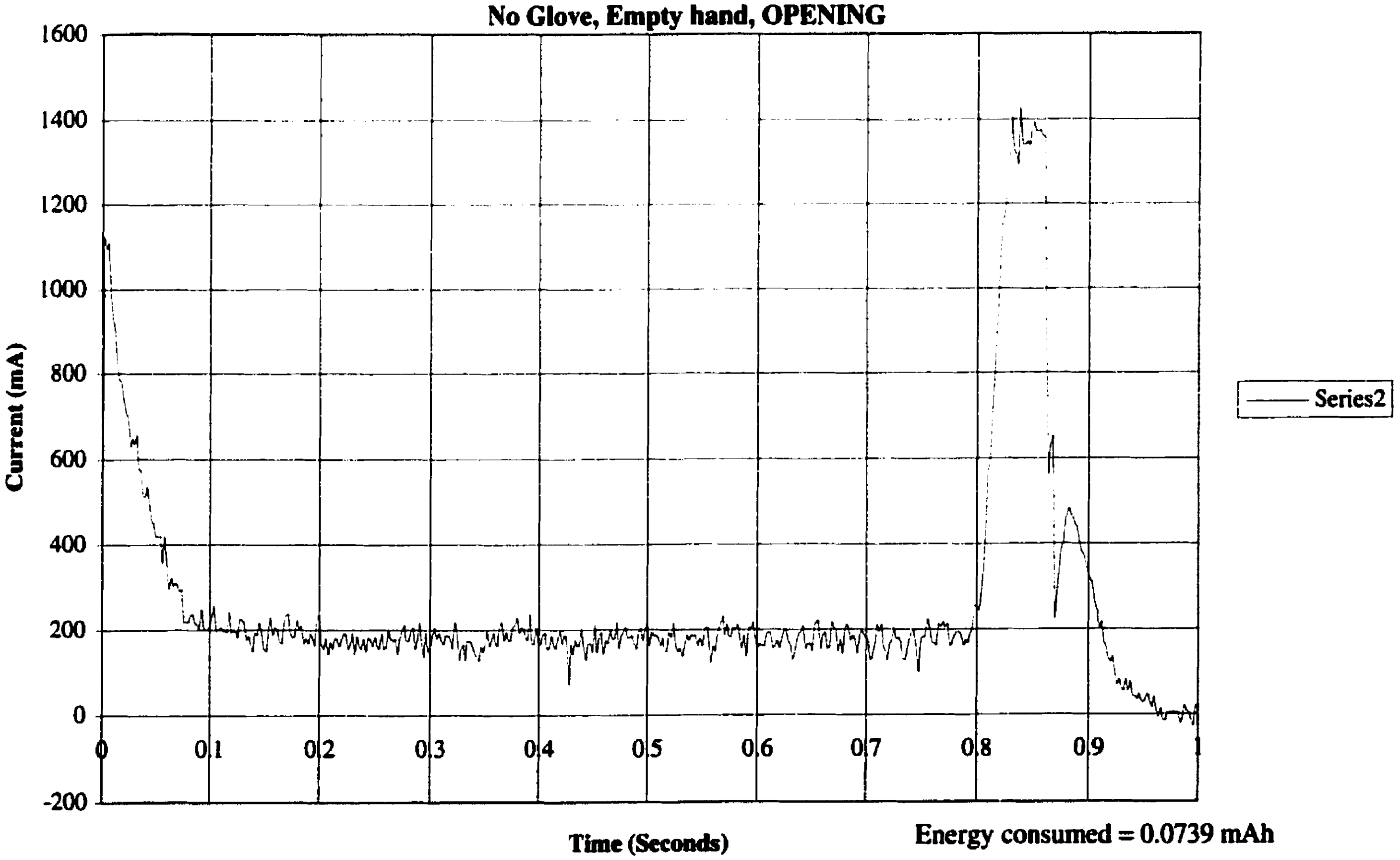
Energy consumed = 0.1379 mAh

GRAPH E15 (VASI 7-11)
Motor Current vs. Time (Averaged, measured at motor)
No Glove, Empty hand, CLOSING



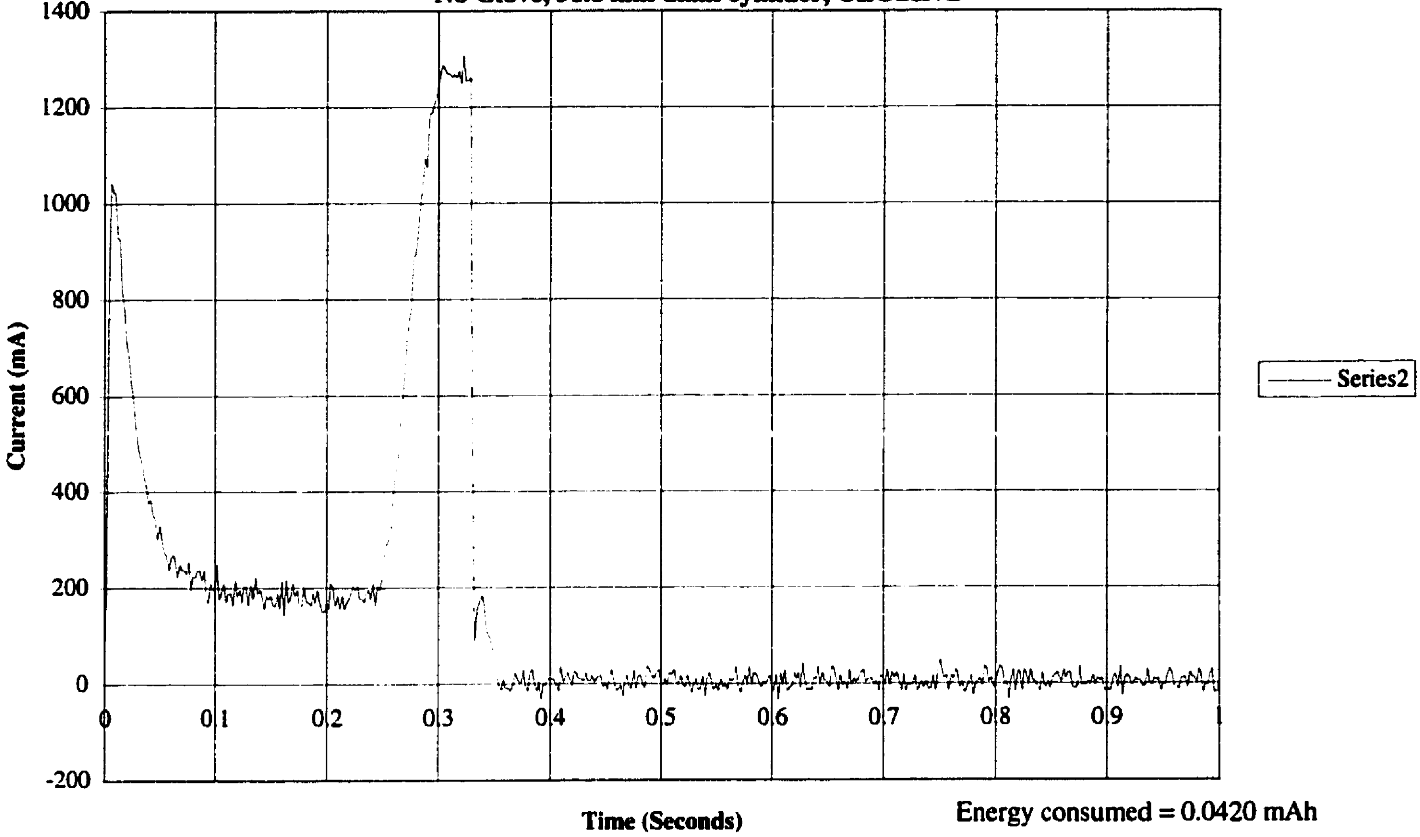
Energy consumed = 0.0643 mAh

GRAPH E16 (VASI 7-11)
Motor Current vs. Time (Averaged, measured at motor)
No Glove, Empty hand, OPENING



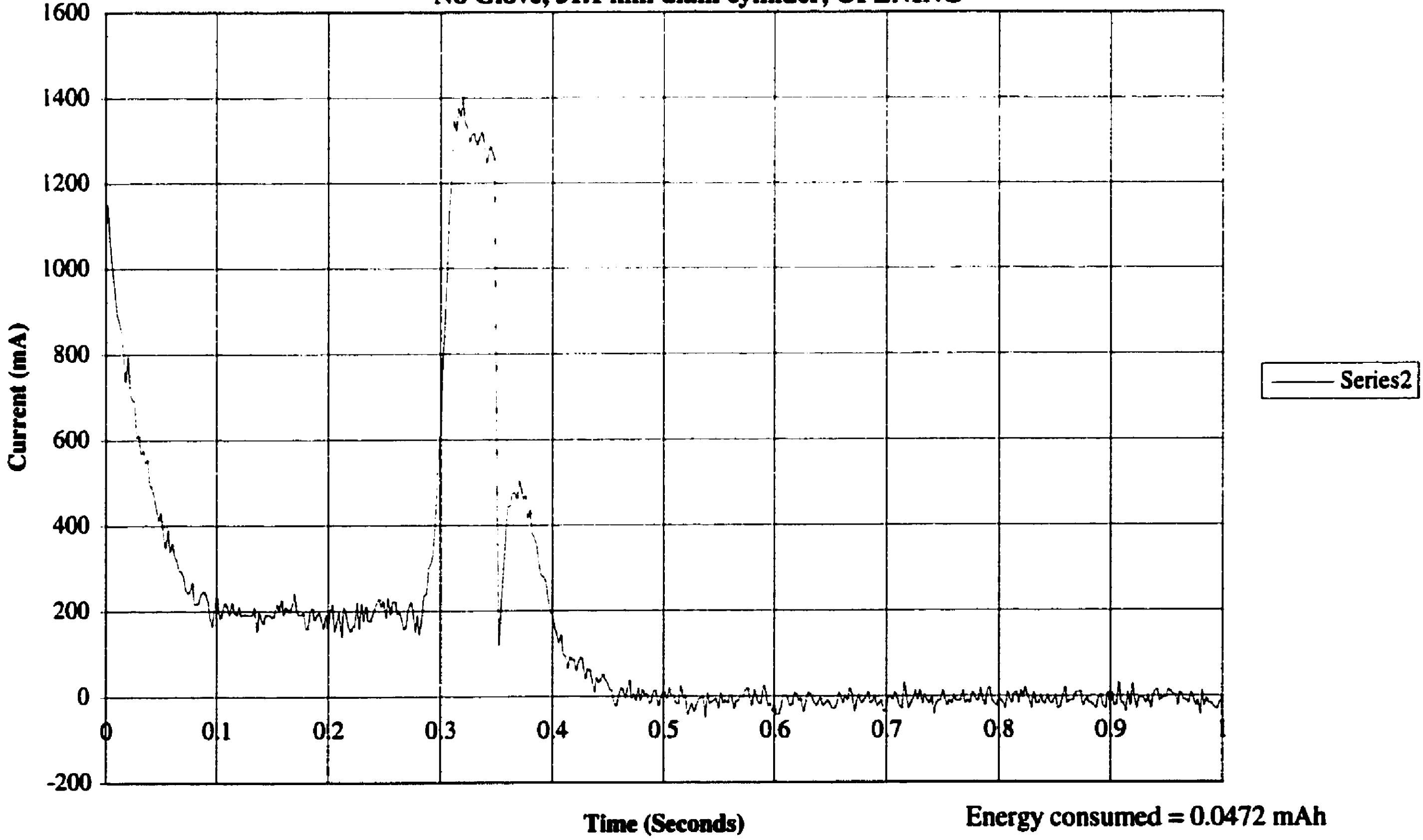
Energy consumed = 0.0739 mAh

GRAPH E17 (VASI 7-11)
Motor Current vs. Time (Averaged, measured at motor)
No Glove, 51.1 mm diam cylinder, CLOSING



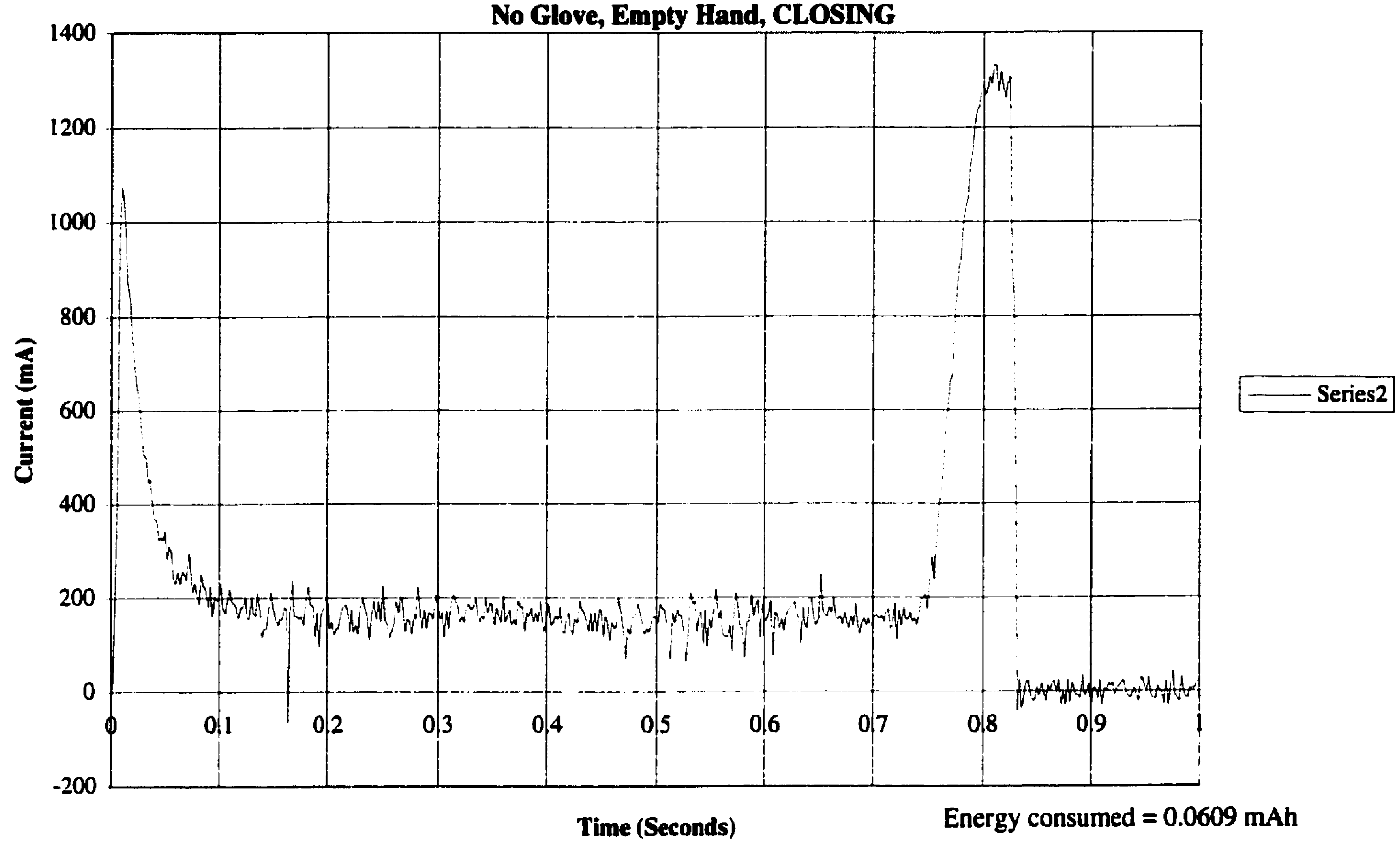
Energy consumed = 0.0420 mAh

GRAPH E18 (VASI 7-11)
Motor Current vs. Time (Averaged, measured at motor)
No Glove, 51.1 mm diam cylinder, OPENING



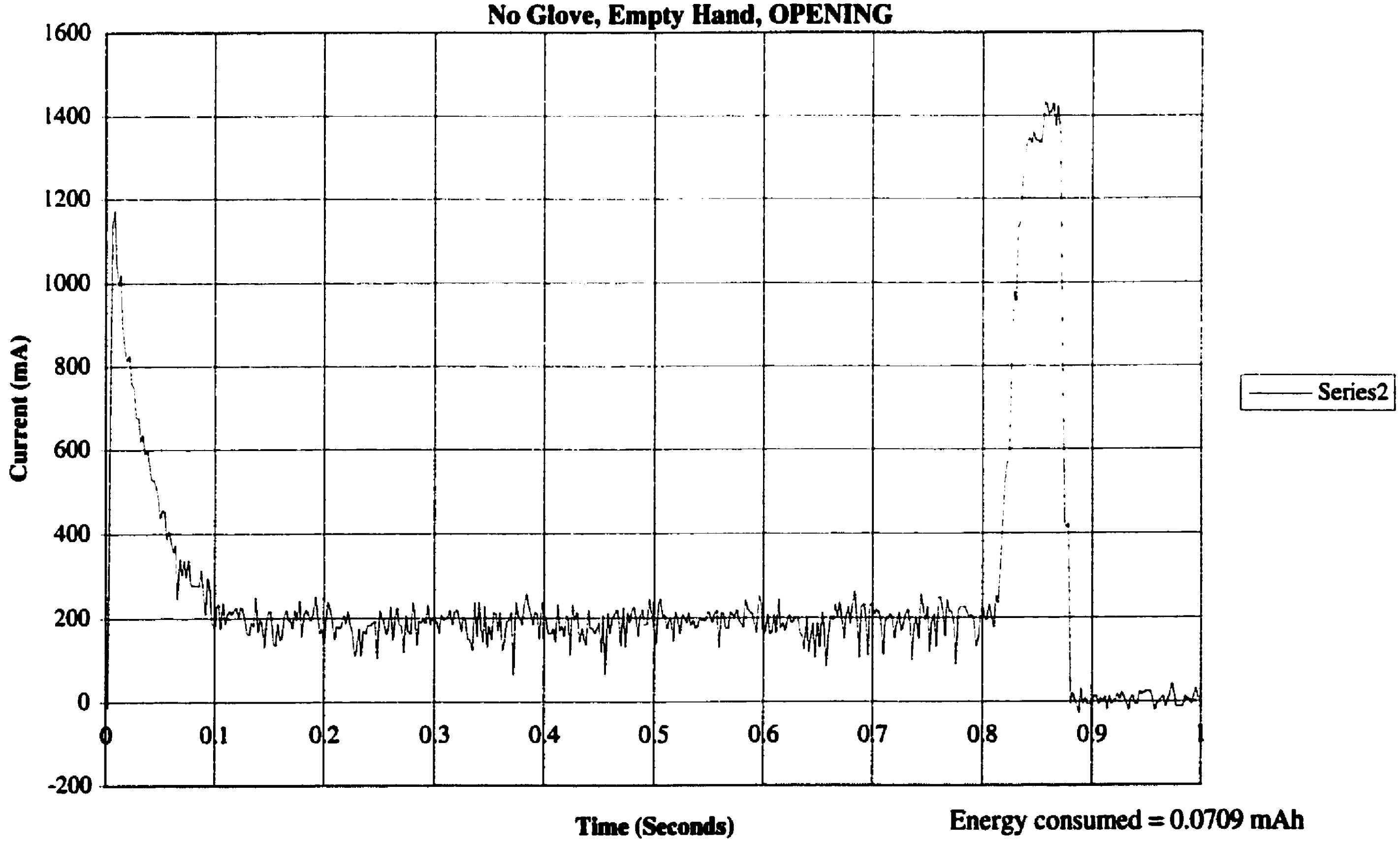
Energy consumed = 0.0472 mAh

GRAPH E19 (VASI 7-11)
Motor Current vs. Time (Averaged, measured at battery)
No Glove, Empty Hand, CLOSING



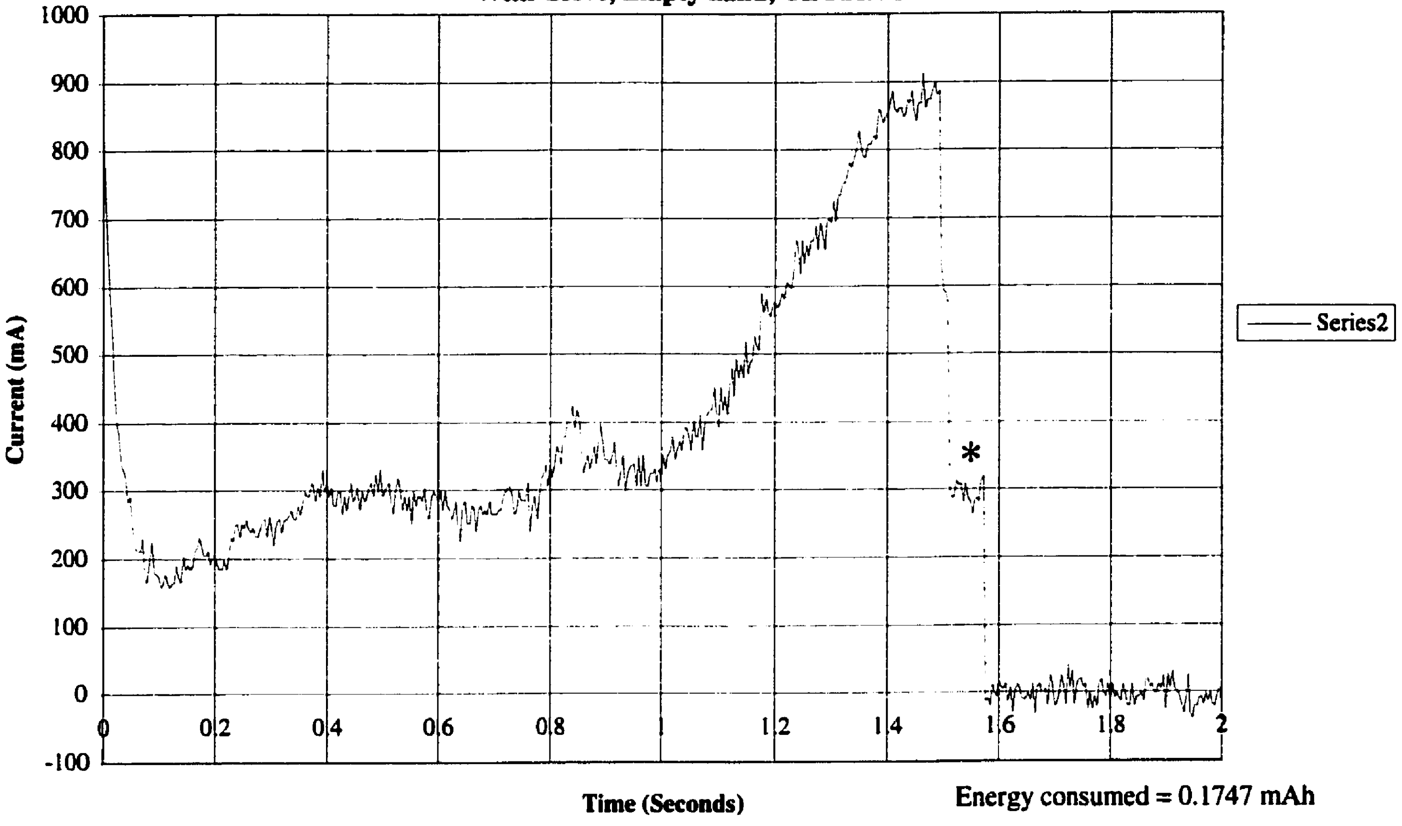
Energy consumed = 0.0609 mAh

GRAPH E20 (VASI 7-11)
Motor Current vs. Time (Averaged, measured at battery)
No Glove, Empty Hand, OPENING



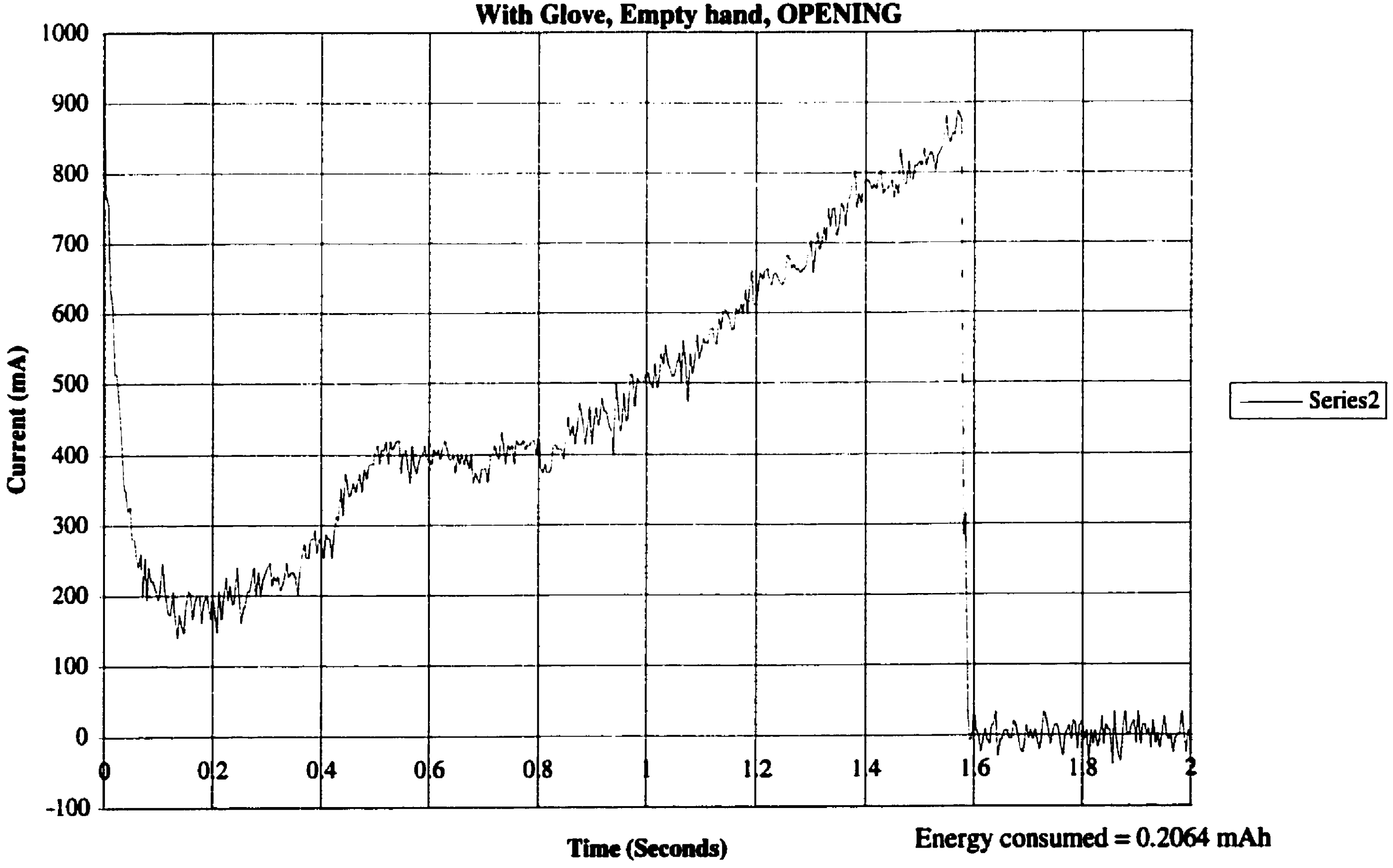
Energy consumed = 0.0709 mAh

GRAPH E21 (Otto Bock 7 1/4)
Motor Current vs. Time (Averaged, measured at battery)
With Glove, Empty hand, CLOSING



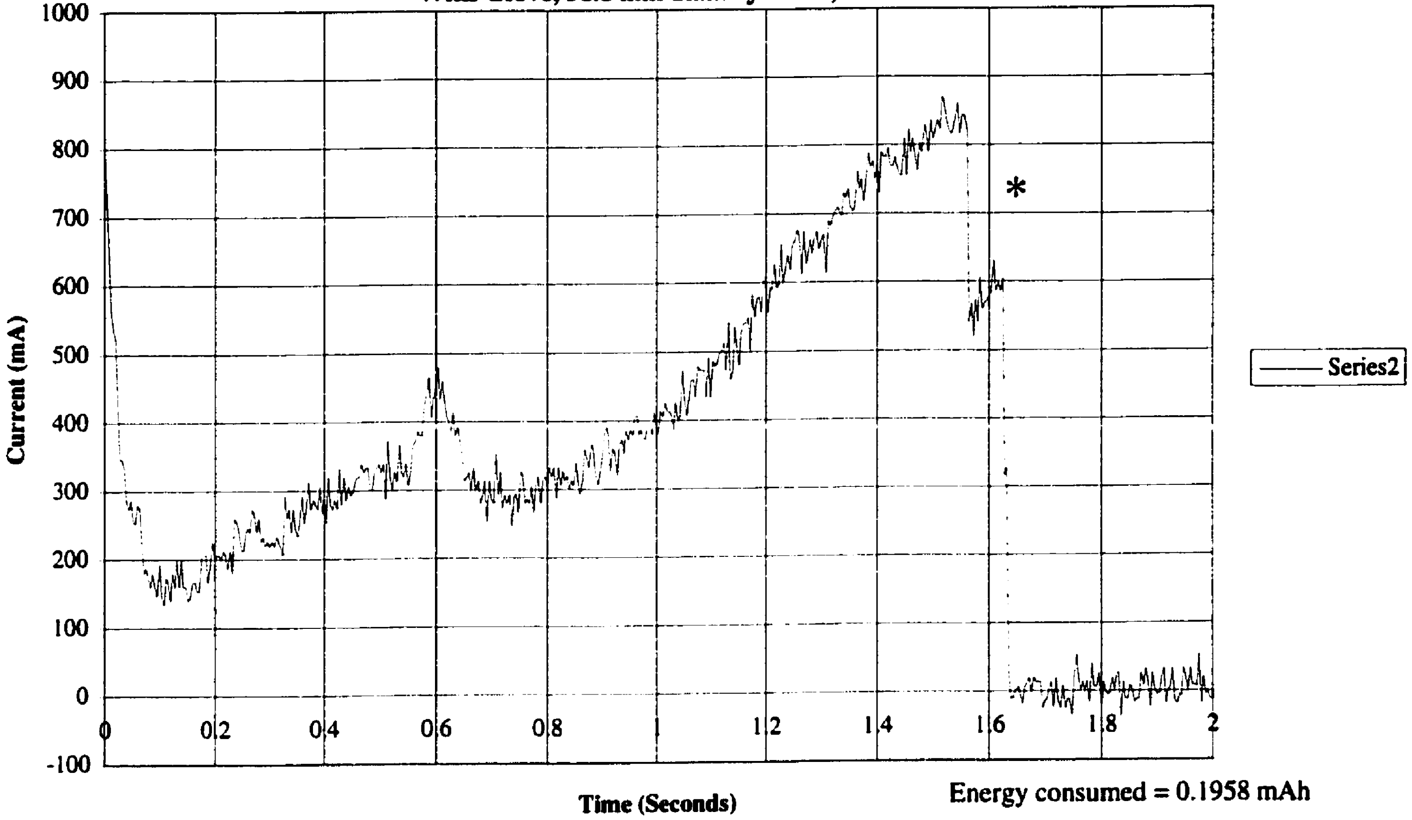
Energy consumed = 0.1747 mAh

GRAPH E22 (Otto Bock 7 1/4)
Motor Current vs. Time (Averaged, measured at battery)
With Glove, Empty hand, OPENING



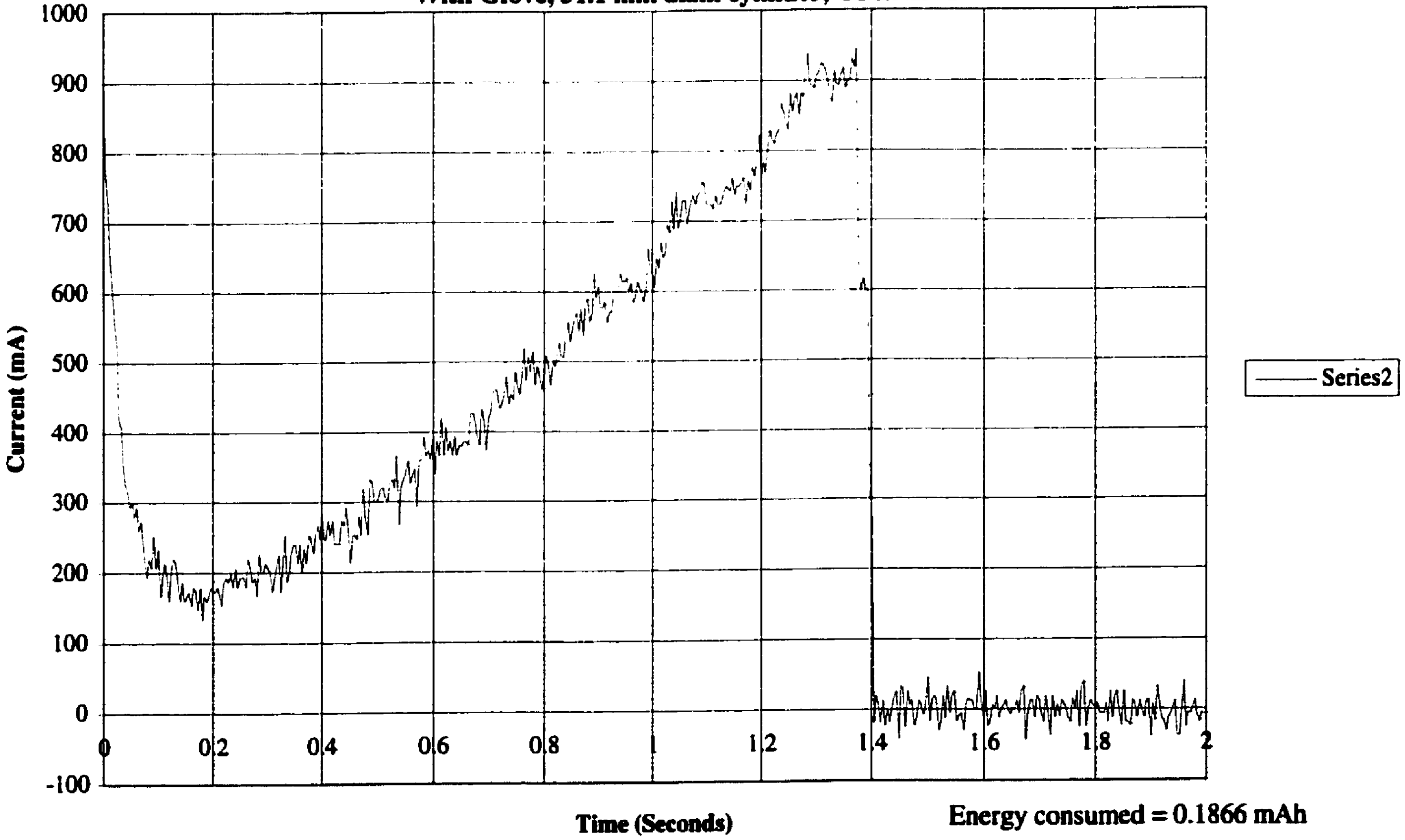
Energy consumed = 0.2064 mAh

GRAPH E23 (Otto Bock 7 1/4)
Motor Current vs. Time (Averaged, measured at battery)
With Glove, 51.1 mm diam cylinder, CLOSING



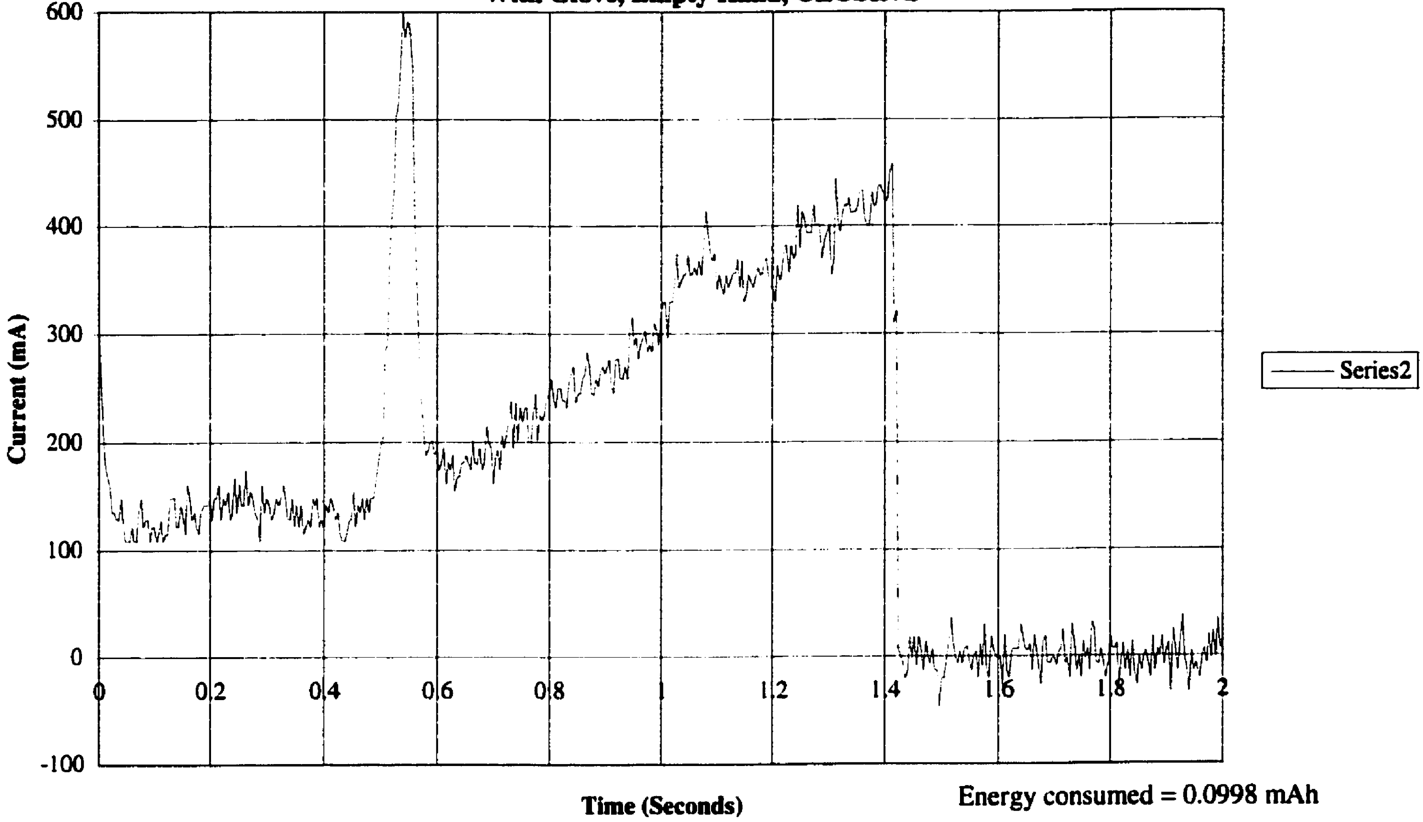
Energy consumed = 0.1958 mAh

GRAPH E24 (Otto Bock 7 1/4)
Motor Current vs. Time (Averaged, measured at battery)
With Glove, 51.1 mm diam cylinder, OPENING



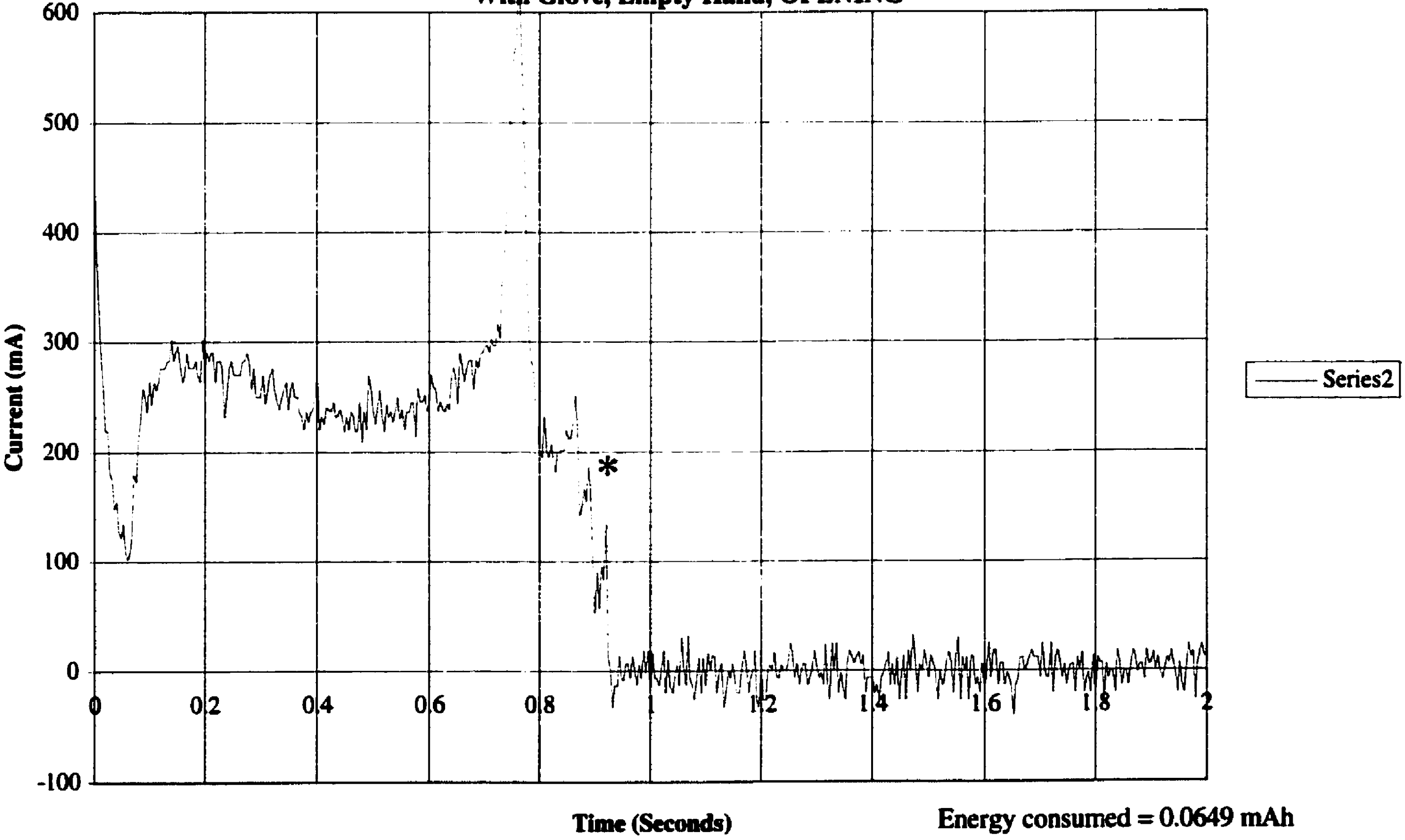
Energy consumed = 0.1866 mAh

GRAPH E25 (Otto Bock 6 1/2)
Motor Current vs. Time (Averaged, measured at battery, Electrode activation)
With Glove, Empty Hand, CLOSING



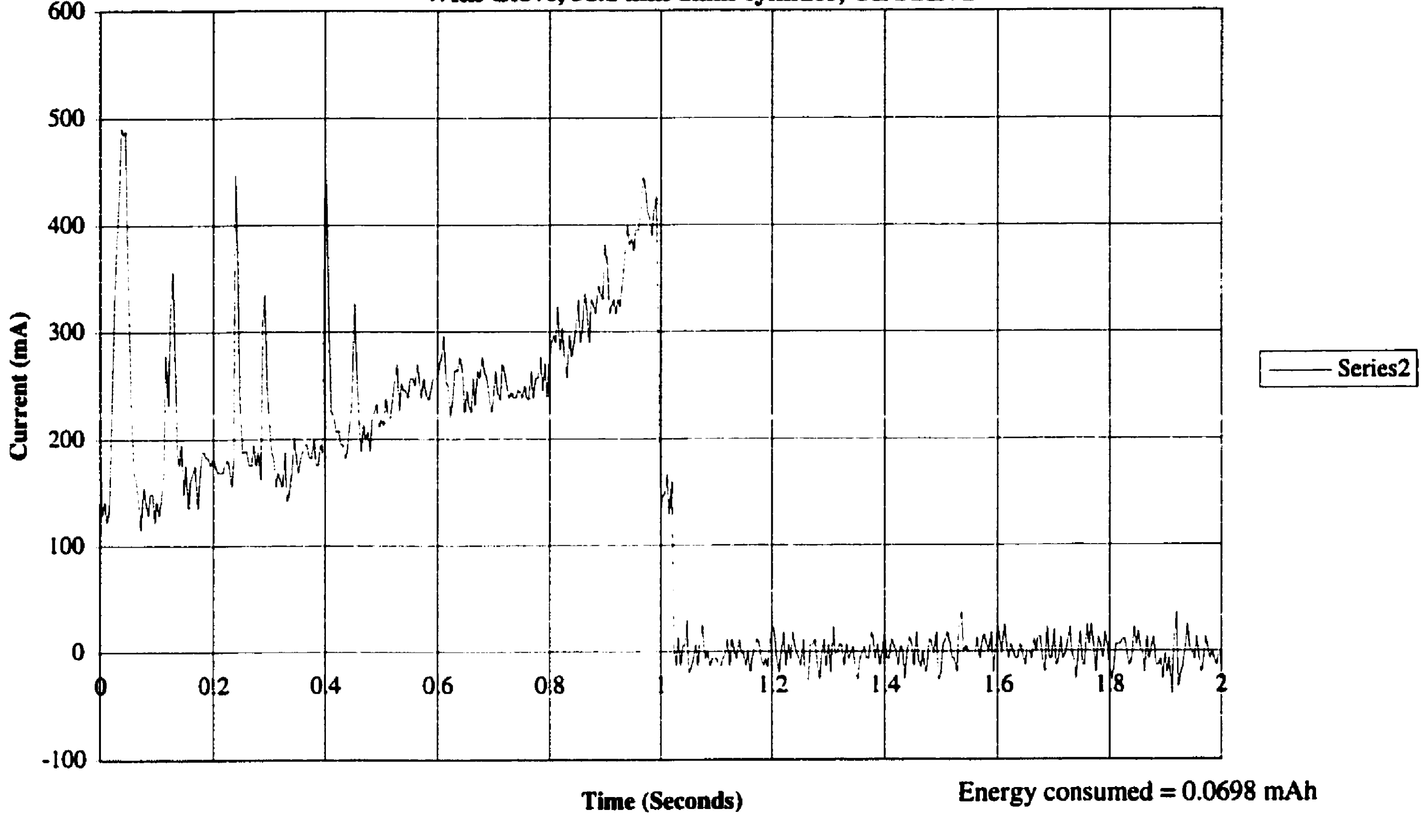
Energy consumed = 0.0998 mAh

GRAPH E26 (Otto Bock 6 1/2)
Motor Current vs. Time (Averaged, measured at battery, Electrode activation)
With Glove, Empty Hand, OPENING



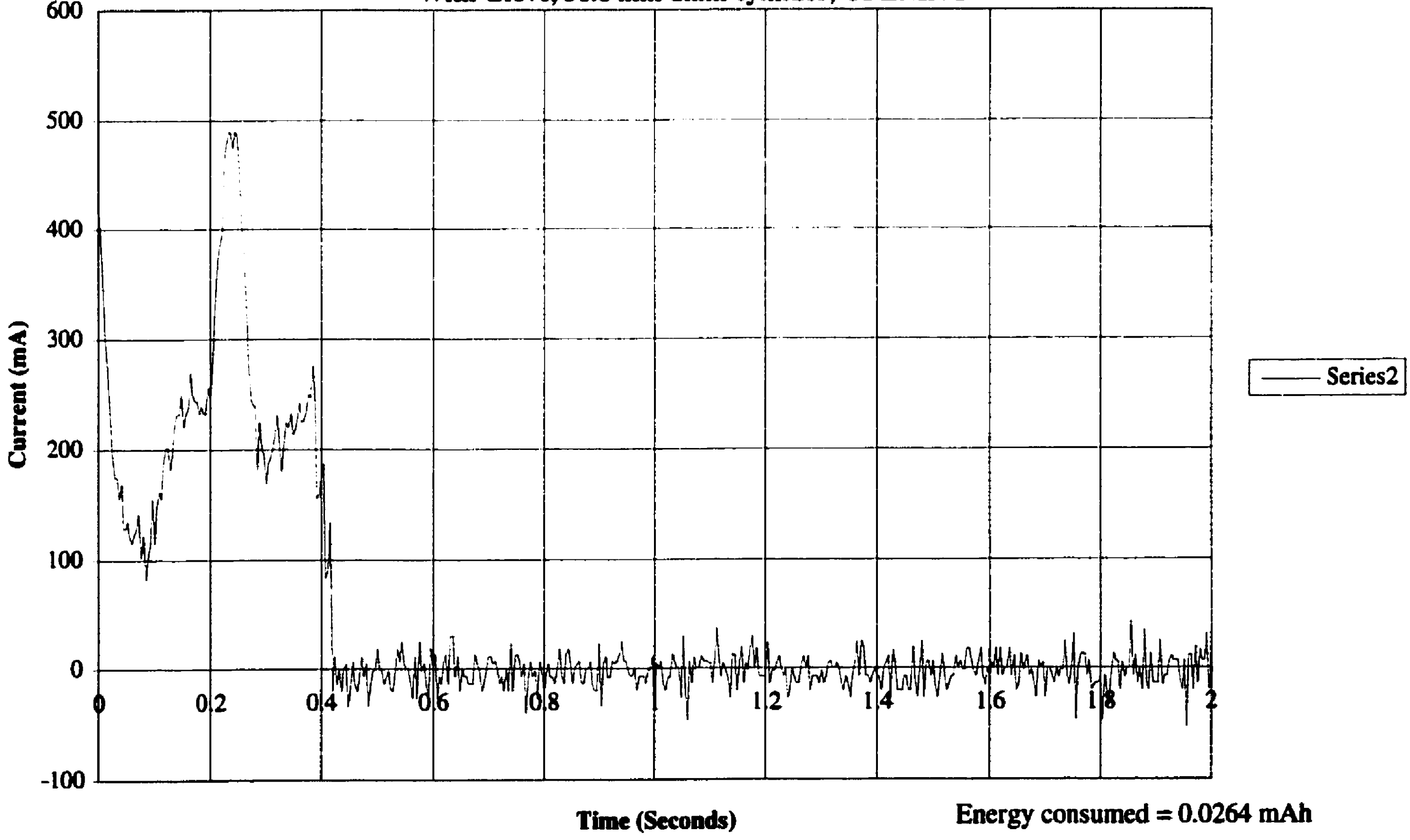
Energy consumed = 0.0649 mAh

GRAPH E27 (Otto Bock 6 1/2)
Motor Current vs. Time (Averaged, measured at battery, Electrode activation)
With Glove, 51.1 mm diam cylinder, CLOSING



Energy consumed = 0.0698 mAh

GRAPH E28 (Otto Bock 6 1/2)
Motor Current vs. Time (Averaged, measured at battery, Electrode activation)
With Glove, 51.1 mm diam cylinder, OPENING



Energy consumed = 0.0264 mAh

Appendix F.1:
MicroMo 1724E 6 Volt Motor Specifications:

Electrical Specifications:

Characteristic:	Units:	Value:
Supply Voltage nom.	(Volts)	6
Armature Resistance	(Ohm) ±12%	4
Maximum Power Output	(Watts)(1)	2.25
Maximum Efficiency	(%)(1)	81
No Load Speed	(RPM) ±12%(1)	8000
No Load Current	(mA) ±50%(2)	15
Friction Torque (@No Load Speed)	(oz-in)	0.016
Stall Torque	(oz-in)(1)	1.49
Velocity Constant	(RPM/Volt)	1347
Back EMF Constant	(mV/RPM)	0.743
Torque Constant	(oz-in/Amp)	1.00
Armature Inductance	(mH)	0.106

Mechanical Specifications:

Mechanical Time Constant	(mS)(1)	8
Armature Inertia	($x10^{-4}$ oz-in-Sec^2)	.143
Angular Acceleration	($x10^3$ Rad/Sec^2)(1)	104.7
Radial Bearing Play	(measured at bearing)	less than 0.3mm
Axial Bearing Play	(measured at bearing)	less than 0.2mm
Thermal Resistance, Rotor to Case	(°C/W)	8
Thermal Resistance, Case to Ambient	(°C/W)	33
Maximum Shaft Loading,		
Radial (@ 3000 RPM)	(oz)	4.3
Axial (Standing Still)	(oz)	72
Weight	(oz)	0.93
Rotor Temperature Range	(°C)	-30°C to 100°C

(1) Specified at nominal supply voltage

(2) Specified with shaft diameter = 1.5mm at no load speed

-Reproduced from MicroMo 1996 catalogue-

Appendix F.2:
Current vs Time Data Collection Procedures

The data were collected using a Fluke PM3380A Autoranging Combiscope oscilloscope. The oscilloscope was first calibrated using the calibration pin which produced a square wave of given voltage, at a given frequency. Next, an appropriate voltage/division interval and a time/division interval were selected depending on the motor measured. The oscilloscope would produce a graph on its screen, in millivolts vs milliseconds. After a graph was produced, the 'RUN/STOP' button was pressed to stop the sampling, otherwise the graph would be overwritten a few seconds later. While the graph was stopped, the 'CURSOR' button was pressed, allowing for a more carefully examination of the data. With this feature, two 'virtual probes' were available for use, represented on the screen as lines. By moving the lines right or left, along the graph data, the oscilloscope displayed the difference in voltage and the difference in time between the two probes. These probes provided important information, needed to calibrate the data after it was downloaded to a computer. The 'virtual probes' were used for two main measurements. Firstly, one 'virtual probe' was placed on the first major peak of the graph and the other 'virtual probe' on the last major peak. The exact time between the two peaks and the difference in voltage between the two peaks, was recorded. Secondly,one 'virtual probe' was placed on the highest peak and the other in an area on the graph where the electrical activity was known to have stopped(usually at the tail end of the graph), and was presumed to have an approximately zero volt value. The difference in voltage was recorded and assuming that one 'virtual probe' was reading zero, this value should have been the peak voltage in the graph.

The oscilloscope was able to use regular laser printers or plotters, to produce printouts of the graphs that it displayed on its screen. There were a number of printer formats that could be chosen from. However, instead of printing directly to a printer or plotter, these formats could be downloaded onto a computer via an RS232 connection. A printer picture of the data was not as desireable as the actual raw data itself, therefore, the raw data was downloaded for further processing. The printer formats scrambled the raw data quite a bit, but one of the plotter formats was quite useful since it listed the data points sequentially. The plotter HPGL® data format was used. This format was useful, because it recorded the data sequentially, in a (x,y) point format, where the x was incremented one by one, and the y was a scaled value of the millivolt data.

It may be of some use for others to download oscilloscope data in the future, therefore a very detailed explanation on how to do this is provided. The HPGL® data file was downloaded to the computer, using the the communications port. The RS232 port on the back of the oscilloscope was 9-pin and the communications port on the computer was 25-pin. Also, a null-modem was required in between the connection. Once downloaded, there was some initial and final extraneous data in the HPGL® file, but these extraneous data were easily deleted. This was done using any text editor. The HPGL® file was loaded and the start of the data was found (it was in the same place for all the files). Anything above the start point was highlighted with the mouse and deleted. The end of the data stream was then found and anything after the end was highlighted and deleted. This process was quite easy and took about 20 seconds per file. The data then consisted of a stream of numbers, each separated by a comma, in the following format:(x,y,x,y,x,y,x,y,x,y,...). Depending on the data processing software, this format may or may not be acceptable. For Excel, if this format was loaded in, it would place all the data into the first row, in the order described. Unfortunately, this was not very useful for creating graphs or processing. Therefore, since Excel was used, the text file was altered with one more step. The data was grouped into 10 pairs per line, with a <Return> at the end of each line. This was done by going to the top right corner of the file, counting out 10 pairs of data and pressing the <Return> key. Then the <Left arrow key> was pressed once, and then the <Down arrow key> once, and the cursor was then directly below the previous point on the screen. Then the <Return> key was pressed again, the <Left arrow key> once, the <Down arrow key> once, and so on... The whole process took 30 seconds. What this did, was to introduce a <Return> character into the data file, after every 10 pairs of data. This <Return> character was interpreted as an 'end of the row' marker by Excel. The file was then Re-saved as a text file. When this modified text file was imported into Excel, it placed the data into the worksheet, in the same layout as the text file. That is 10 (x,y) data pairs in the first row, 10 pairs in the second, etc... The data was still not in the format desired, so there were two more steps. Ideally, the data was wanted in such a format that column A and column B hold the x and associated y values respectively, in ascending order of x values. This could be done in a number of ways, but the following procedure, which takes about 45 seconds is recommended. The cut and paste tools from the Edit menu(actually ctrl-x, and ctrl-v) are used. Leaving the first two columns(A &B), 'cut' all the data in the next two columns(C&D), and paste it directly below the last data in the first two columns(A&B). Then cut all the data in the next two columns(E&F) and paste it directly below the last data in first two columns(A&B). Then cut all the data in the next two columns(G&H), etc... When finished, all the data are in columns A & B, however, they are out of order. To correct this, select (highlight) all the data in columns A&B, and choose the 'Sort' option. Sort the data in ascending order, with respect to column A (the x data). Once this is done, the data is in a good format for Excel graphs, multiplication and average processing.

The reason for the 'CURSOR' measurements on the oscilloscope will now be explained.

Those measurements were used to calibrate the graphs created on the Excel worksheet. Depending on the printer data format chosen on the oscilloscope, the actual millivolt values will be represented in different numerical ways. The data stream will not show millivolt values, or time values. The first 'CURSOR' measurements were important because no matter what numerical form the data is stored in, the two maximum values within the data set must represent the two maximum peaks on the oscilloscope screen. Also, the data is not random, but sequential on the x-coordinate. Since the two maximum values can be identified and the time between these two peaks has been recorded from the oscilloscope, the time interval on the graph can be calibrated by a multiplication factor on the x-coordinate data. The second set of 'CURSOR' readings are used to find the approximate zero reading and maximum peak reading. The zero readings on the graphs are characterised by a flat region close to the x-axis. The maximum peak is the highest numerical value in the downloaded data. The voltage between the 'zero line' and the maximum peak were read from the oscilloscope, so the downloaded data can now be multiplied by an appropriate scaling factor, to make it match the original reading. Also, the data may have to be shifted up or down, by adding a constant value to all the data points, so that the 'zero line' of the data is on the x-axis of the graph.

Appendix F.3:
Otto Bock System 2000 hand Specifications:

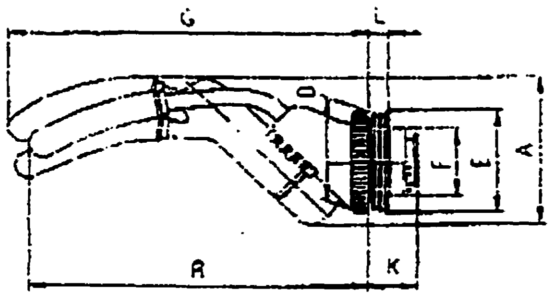
2. MYO-WORKSHOP
May 1995 - Vienna

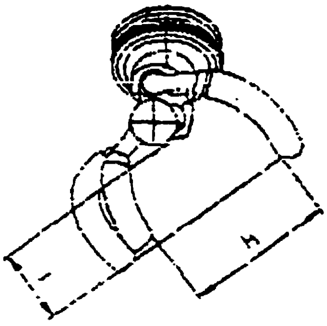
TECHNICAL COMPARISON

OTTO BOCK SYSTEM 2000

SPECIFICATIONS:

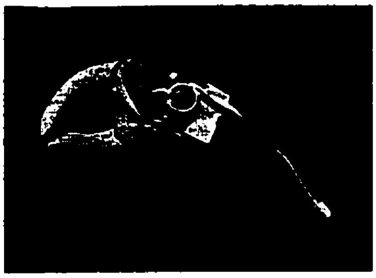
Model		5	5 ½	6	6 ½
Age range (yrs)		0 - 3	3 - 6	6 - 9	9 +
Weight		86 gr	115g	125g	128g
Dimensions (closed position)	KEY	mm	mm	mm	mm
Max. width	(A)	49	53	54	54
Hand body / thumb tip	(B)	77	96	101	110
Lamination ring / thumb tip	(C)	——	——	——	——
Overall wrist diameter	(D)	35	35	39	39
Lamination ring - outside diameter	(E)	34,4	34,4	38,4	38,4
Switching circuit diameter	(F)	25	25	25	25
Max. length / excluding wrist	(G)	80	102	109	120
Max. opening	(H)	33	38	54	59
Finger opening depth	(I)	29	31	32	37
Length of longest finger	(J)	——	——	——	——
Wrist unit	(K)	18	18	18	18
Lamination ring	(L)	6	6	7	7
Nominal operating voltage		4,8 V	4,8 V	4,8 V	4,8 V
Maximum current (motor)		400 mA	400 mA	400 mA	400 mA
Typical current		200 mA	200 mA	200 mA	200 mA
Pinch force (glove on)		15N	35N	45-50N	45-50N
Max. open or close time		1 sec	1 sec	1 sec	1 sec
Angle for wrist Rotation		360°	360°	360°	360°
Slip clutch		no	yes	yes	yes
Grip lock mechanism		yes	yes	yes	yes





Appendix F.4:

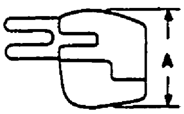
VASI children's hand Specifications:

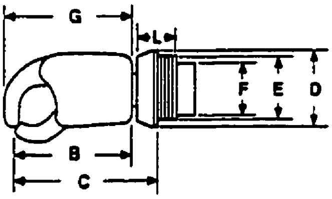


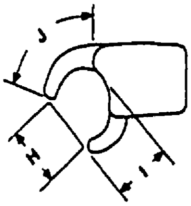
Unique Energy Saver circuit extends the useful life of a single battery charge.

Finger to thumb distance is extra wide to permit better grasp of large objects such as toys.

HAND SPECIFICATIONS					
Age range (yrs.)		**0-3**	**2-6**	**5-9**	**7-11**
Model		VV 0-3	VV 2-6	VV 5-9	VV 7-11
Proportional control - two-muscle		VV 0-3 A3000 PT	VV2-6 A3000 PT	VV 5-9 A2000PT	VV 7-11A2000 PT
Digital control - two-site		VV 0-3 A2000 T	VV 2-6 A2000T		
Digital control - one-muscle		VV 0-3 A2000 C	VV 2-6 A2000 C		
No electronics		VV 0-3 C	VV 2-6 C	VV 5-9 C	VV 7-11 C
No electronics & no wrist		VV 0-3 D	VV 2-6 D	VV 5-9 D	VV 7-11 D
Weight (with harness - no wrist unit/ no glove)		86gm (3.034oz)	126gm (4.444oz)	190gm. (6.702oz)	198gm (6.984oz)
Dimensions		mm. in.	mm. in.	mm. in.	mm. in.
Max. width	A	48 1.90	53 2.10	65 2.58	65 2.57
Hand body / thumb tip	B	55 2.19	67 2.63	87 3.45	91 3.60
Lamination ring / thumb tip	C	67 2.67	80 3.15	100 3.94	103 4.09
Overall wrist diameter	D	33 1.31	40 1.57	40 1.57	40 1.57
Lamination ring - outside diameter	E	29 1.12	37 1.46	37 1.46	37 1.46
Lamination ring - inside diameter	F	24 0.94	30 1.19	30 1.19	30 1.19
Max. length (excluding wrist)	G	59 2.35	70 2.77	94 3.73	98 3.80
Max. opening	H	53 2.09	51 2.00	70 2.75	69 2.70
Finger opening depth	I	31 1.25	37 1.45	36 1.42	44 1.70
Length of longest finger	J	38 1.49	48 1.89	54 2.12	66 2.60
Quiescent current		<60 µA	<60 µA	<20 µA	<20 µA
Nominal operation voltage		4.8 V 6 V	4.8 6 V	4.8 V 6 V	4.8 V 6 V
Maximum current (motor)		260mA	340mA	1.4 A	1.4 A
Pinch force		3.5 LB 4.5 LB	5.0 LB 7.0 LB	6.0 LB 9.5 LB	6.5 LB 8.0 LB
Maximum open time		1.5 sec 1.1sec	1.2 sec 0.9 sec	1.4 sec 1.0 sec	1.1 sec 0.9 sec
Maximum close time		1.5 sec 1.1 sec	1.2 sec 0.9 sec	1.4 sec 1.0 sec	1.1 sec 0.9 sec







The VV series electric hands, known for their quality and reliability, have been designed for child amputees in the one to eleven year age range. The "VV 0-3", "VV 2-6", "VV 5-9" and "VV 7-11" are aesthetic and lightweight yet can withstand the rigors of child play because of injection molded construction techniques.

All four of VASI's hands are compatible with the most popular switch and myoelectric control systems from VASI, Otto Bock and other manufacturers. Connection is made easy with the commonly used Otto Bock 4-pin type connectors. Standard rotation wrists (long), allow the hand to be passively positioned. A wide variety of other wrist units are available: call for information. Also, inquire about VASI's new children's powered wrist designed to improve prosthetic function.

The totally modular design simplifies maintenance. All electronic components are packaged to permit economical repair or replacement. Similarly, the integrated motor and gear housing can be easily removed and replaced in minutes.

An optional integrated power-bridge and energy-saver circuit allows the prosthetist to easily customize the hand to the child's needs for one or two-muscle or two-muscle proportional operation. Contact your VASI representative for more details.

VASI WRIST UNITS		
Drawing #	**Weight**	**Wrist depth: L**
No Rotation - Oval		
VVH-59112 205-536 VVH-03125	16gm 0.564oz 12gm 0.423oz 10gm 0.353oz	0.21" 5.33mm
No Rotation - Round		
VVH-59094 205-601 VVH-03082	16gm 0.564oz 14gm 0.494oz 12gm 0.423oz	0.21" 5.33mm
Standard Rotation - Short		
VVH-59093 205-458 VVH-03090	40gm 1.411oz 38gm 1.340oz 30gm 1.058oz	0.628" 15.95mm
Standard Rotation - Long		
VVH-59097 205-456 VVH-03078	36gm 1.270oz 34gm 1.200oz 26gm 0.917oz	0.768" 19.51mm
Standard Rotation - Elbow		
VVH-59103 205-534 VVH-03084	42gm 1.481oz 40gm 1.411oz 40gm 1.411oz	1.208" 30.68mm
Omni-Wrist - VASI Hands		
VVH-59113 205-537 VVH-03130	34gm 1.200oz 32gm 1.130oz 32gm 1.130oz	0.806" 20.47mm
Flexi-Wrist		
FW - 59 FW - 26 FW - 03	28gm 0.988oz 26gm 0.917oz 24gm 0.847oz	0.636" / 21.23mm 0.836"/ 21.23mm 0.886"/ 22.50mm
Electric Wrist Rotator	**Call**	

Appendix G:
Pull-Out Test Results

Raw data, all 35 trials were randomized
All results measured in grams

1/2" Delrin sphere

Trial #1	906	
Trial #2	1256	
Trial #3	1074	
Trial #4	1310	
Trial #5	1340	
sample mean	1177.2	grams
	2.58984	lbs
s. standard dev.	183.4045	grams
	0.40349	lbs

1" Delrin sphere

Trial #1	1350	
Trial #2	944	
Trial #3	1766	
Trial #4	1362	
Trial #5	1054	
sample mean	1295.2	grams
	2.84944	lbs
s. standard dev.	320.404744	grams
	0.70489044	lbs

7/8" Delrin flat block

Trial #1	2006	
Trial #2	2162	
Trial #3	1676	
Trial #4	1608	
Trial #5	2076	
sample mean	1905.6	grams
	4.19232	lbs
s. standard dev.	248.062089	grams
	0.5457366	lbs

1 1/4" wood sphere

Trial #1	1472	
Trial #2	1466	
Trial #3	1080	
Trial #4	1440	
Trial #5	2256	
sample mean	1542.8	grams
	3.39416	lbs
s. standard dev.	431.369	grams
	0.949012	lbs

2 3/16" wood sphere

Trial #1	1892	
Trial #2	1846	
Trial #3	2478	
Trial #4	2088	
Trial #5	2342	
sample mean	2129.2	grams
	4.68424	lbs
s. standard dev.	276.183272	grams
	0.6076032	lbs

3" wood sphere

Trial #1	2522	
Trial #2	2482	
Trial #3	2198	
Trial #4	2148	
Trial #5	2280	
sample mean	2326	grams
	5.1172	lbs
s. standard dev.	168.029759	grams
	0.36966547	lbs

2" acrylic cylinder

Trial #1	2890	
Trial #2	3156	
Trial #3	2456	
Trial #4	3010	
Trial #5	3156	
sample mean	2933.6	grams
	6.45392	lbs
s. standard dev.	289.2936	grams
	0.636446	lbs

Appendix G:
Pull Out Test Pictures

Figure G1. Grip of 1/2" Delrin Sphere

Figure G2. Grip of 1" Delrin

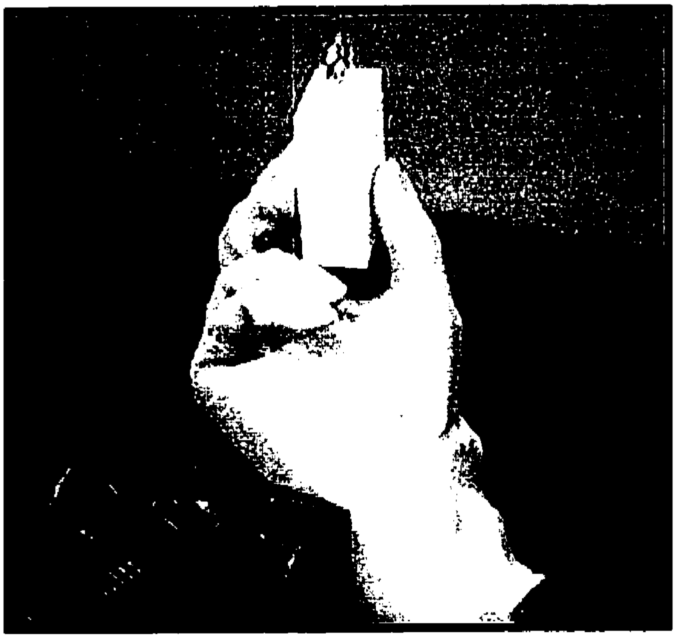


Figure G3. Grip of 7/8" Delrin Block

Figure G4. Grip of 2" Acrylic Cy

Appendix G:
Pull Out Test Pictures


Figure G5. Grip of 1 1/4" Wood Sphere

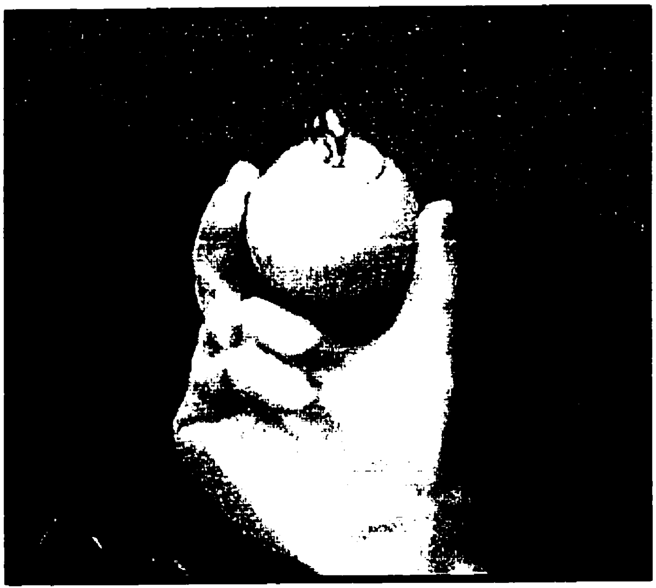


Figure G6. Grip of 2 3/16" Wood Sphere

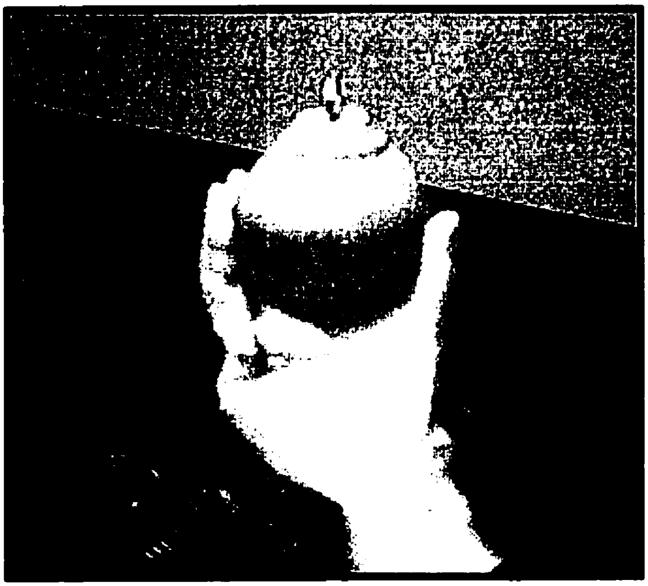


Figure G7. Grip of 3" Wood Sphere