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**Optimization and automation of stimulus map synthesis for
upper extremity FNS**

Kilgore, Kevin Lloyd, Ph.D.

Case Western Reserve University, 1991

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OPTIMIZATION AND AUTOMATION OF STIMULUS MAP SYNTHESIS
FOR UPPER EXTREMITY FNS

by

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Submitted in partial fulfillment of the requirements
for the Degree of Doctor of Philosophy

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August, 1991

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OPTIMIZATION AND AUTOMATION OF STIMULUS MAP SYNTHESIS FOR UPPER EXTREMITY FNS

Abstract

by

KEVIN LLOYD KILGORE

Functional neuromuscular stimulation (FNS) has been used to power an open-loop upper extremity neuroprosthesis. A principle issue in the implementation of the neuroprosthesis is the synthesis of the stimulus map, which relates the input control signal to the output stimulus level applied to each electrode. The goal of this project was to develop a method for synthesizing the optimum stimulus map, which is defined as the stimulus map for which the resulting grasp output most closely matches the desired grasp output. Optimization is achieved by 1) compensating for the influence of the electrode-position dependent recruitment properties on the grasp output, and 2) minimizing the influence of the time and task dependent variables on the grasp output. The time and task dependent variables are fatigue, object size and extremity position. Compensation for the position dependent recruitment properties was achieved by the development of an

external moment grasp synthesis procedure (EMGSP) for stimulus map synthesis. The EMGSP describes the interaction between the active moments produced by electrical stimulation, the passive joint moments, and the resulting total joint moment and angle. The EMGSP was used to develop the stimulus map for three paralyzed subjects, and in all cases the EMGSP-generated grasp had lower errors than grasp patterns developed using the previously implemented rule-based method of stimulus map synthesis. The EMGSP was successful in compensating for the influence of the position dependent recruitment properties on the grasp pinch force.

Minimization of the influence of the time and task dependent variables on the grasp output was accomplished using a simulation of the EMGSP. The results indicate that proper selection of the assumed contact point and minimization of cocontraction reduces the grasp output error. Further improvement in grasp output can be obtained by rejecting electrodes with high gain, thumb flexor electrodes with positive output stiffness (flexion force increases as thumb is extended) and thumb extensor electrodes with negative output stiffness. The outcome of this project is a method for optimizing and automating the synthesis of the stimulus map used in open loop upper extremity FNS.

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ABBREVIATIONS

Abductor Pollicis Brevis	AbPB
Abductor Pollicis Longus	AbPL
Adductor Pollicis	AdP
Carpometacarpal	CMC
Extensor Digitorum Communis	EDC
Extensor Pollicis Brevis	EPB
Extensor Pollicis Longus	EPL
External Moment Model	EMM
External Moment Grasp Synthesis Procedure	EMGSP
First Dorsal Interosseous	1DI
Flexor Pollicis Brevis	FPB
Flexor Pollicis Longus	FPL
Functional Neuromuscular Stimulation	FNS
Interphalangeal	IP
Interpulse Interval	IPI
Joint Moment Recruitment Curve	JMRC
Median Thenar Intrinsic	MTI
Metacarpophalangeal	MP
Microsecond	μ S
Milliamp	mA
Millisecond	mS
Newtons	N
Opponens Pollicis	OP
Pulse Width	PW
Stimulus Period	SP

I. INTRODUCTION

Injury at the cervical level, resulting in quadriplegia, leaves the individual dependent on others for assistance to perform even the most basic tasks. Providing these individuals with increased independence and function is extremely important to improving their quality of life. Although splints and special adaptive equipment can be utilized to provide some function, usually these devices must be put on by others, are cosmetically unacceptable and often limited in function. Functional neuromuscular stimulation is an attractive alternative because it makes use of the individual's own musculature, is more cosmetically acceptable and has the potential for much more adaptable function.

The objective of this research was to increase the independence of C5 and C6 level quadriplegic individuals by restoring grasp and release using electrical stimulation of paralyzed muscles [1,13,27,33,42,43]. In the neuroprosthetic system, muscles which are paralyzed due to spinal cord injury are implanted with electrodes for delivery of a graded electrical stimulus for activation and control [5]. The resultant movement is controlled by command signals from remaining voluntary movements [19]. A controller/stimulator is responsible for converting the command control

signal to the appropriate stimulus levels for each electrode so that the desired grasp pattern is achieved [3]. Figure I.1 shows a block diagram of the components of this system. Each component is described in the following paragraphs.

Control of the neuroprosthesis is provided by the subject's remaining voluntary movement. Typically this has taken the form of shoulder elevation/depression and retraction/protraction [19]. Other methods of control have been used, including switches operated by the contralateral arm, EMG signals from neck muscles, wrist movement (for subjects with active wrist control), and voice control [33]. Control of the neuroprosthesis involves two types of signals. The first type of signal is a logic signal to control system states (on/off, grasp mode, lock/unlock). The second type of signal, a proportional signal, is used to control the degree of hand opening and closing. When shoulder movement is used for control, shoulder elevation/depression typically provides the proportional signal. Shoulder movement is transduced using a two-degree-of-freedom joystick taped to the chest, with a rod extending to the shoulder. A chest switch provides a logic signal for system on/off and grasp mode selection. Lock and unlock of the hand is obtained by initiating a quick movement of the shoulder. This movement is detected by normalizing the shoulder velocity

Figure I.1. Block diagram of the presently implemented upper extremity neuroprosthesis. The primary components are the command signal obtained from the patients voluntary motion, the controller/stimulator containing the stimulus map, and the electrodes implanted in the paralyzed forearm and hand musculature.

to the movement size [19]. The lock feature allows the subject to hold an object and freely move both shoulders and arms.

The proportional control signal determines the stimulus level to each electrode. The stimulus delivered to each muscle is a balanced charge biphasic pulse. The stimulus is a rectangular regulated current cathodic pulse that is followed by an exponentially decreasing anodic pulse. The stimulus is delivered through electrodes implanted in the forearm and hand.

Two types of electrodes have been used: intramuscular [37] and epimysial [11,22]. The intramuscular electrodes are used as part of a percutaneous system. They are single strand, multi-filament type 316 stainless steel wire insulated with teflon and wound into a helical configuration. One centimeter of the wire is de-insulated to provide the stimulating portion. These electrodes can be inserted into the muscle using a hypodermic needle, with the lead passing percutaneously through the skin. The epimysial electrodes are used with an implanted stimulator and require surgical exposure for placement. The electrode is a Pt-Ir disk with a silicon and dacron backing, and is sutured to the muscle.

Muscles which are electrically excitable for functional use have an upper motor neuron lesion in which the lower motor neurons are at least partially intact. If the lower motor neurons are damaged (denervation), the

muscle cannot be excited at safe stimulus levels using internal electrodes and will be unavailable for use in the neuroprosthesis. If denervation occurs in a muscle necessary for function, tendon transfer of an innervated but paralyzed muscle can be used to provide a motor for the desired movement [21,22].

Muscle contraction strength is graded through either temporal or spatial summation. When muscles are electrically stimulated, temporal summation is achieved by increasing the frequency of stimulation. Spatial summation is achieved by either increasing the stimulus pulse width or amplitude. The method of force modulation used in the current neuroprosthesis is spatial summation achieved by varying the pulse width of stimulation. The stimulus amplitude is maintained at a constant current of 20mA. The stimulus period (inverse of frequency) is typically 60 to 80mS. This value is chosen as a compromise between minimizing the period to produce a fused contraction and maximizing the period to reduce fatigue.

Grasp patterns are developed by stimulating the available muscles in a coordinated fashion. The grasp output is defined as the positions and forces generated by each joint of the hand as a function of the proportional control signal. Two grasp patterns are provided to each subject, a lateral

grasp and a palmar grasp. In the lateral grasp, the fingers are flexed while the thumb is extended over the initial 20% of the command range. Thumb extension decreases linearly from 20 to 60% command, where contact with the index finger occurs. Thumb pinch force is increased linearly from 60% to 100% command. In the palmar grasp, the thumb is posted in abduction and the fingers begin in full extension at 0% command. The fingers are flexed linearly to contact the thumb at 50% command, at which point the finger force increases linearly.

The muscles utilized for the lateral grasp are the adductor pollicis (AdP), extensor pollicis longus (EPL), extensor digitorum communis (EDC), and flexor digitorum profundus (FDP). The AdP is used to provide thumb pinch, and is sometimes augmented by stimulation of the flexor pollicis brevis (FPB) and flexor pollicis longus (FPL). The FPL is the only flexor of the thumb IP joint. Flexion of the IP joint, however, can be detrimental to the lateral grasp and therefore the FPL is typically used only when the thumb IP joint has been surgically fused. The EPL is the primary thumb extensor and is usually recruited in conjunction with the extensor pollicis brevis (EPB). The flexor digitorum superficialis (FDS) is often added to provide additional finger flexion.

In the palmar grasp, the abductor pollicis brevis (AbPB) is used to

place the thumb in opposition. The EDC is used for finger extension and the FDS is used as the primary finger flexor. The FDP is often added to provide addition grip strength.

The relationship between the proportional input command signal and the stimulus level to each electrode is known as the stimulus map. Each electrode/muscle combination exhibits different characteristics, and therefore this map must be generated individually for each subject. The goal of the stimulus map synthesis process is that the grasp output matches the desired grasp output, or grasp template. Realization of this goal is made difficult due to the many factors that affect the grasp output resulting from electrical stimulation. These factors have been identified by analyzing the components of the hand grasp neuroprosthesis, as described in the following paragraphs.

Grasp output resulting from electrical stimulation of paralyzed muscle depends not only on the level of contraction of each stimulated muscle, but on many other factors as well. The components of the hand grasp neuroprosthesis are shown in Figure 1.2. The input proportional command signal serves as an index to the stimulus map to determine the stimulus level delivered to each electrode. The stimulus field produced by the stimulus pulse results in excitation of peripheral nerves innervating various

Figure 1.2. Generation of the grasp output using electrical stimulation. The proportional input command signal is translated into the stimulus level to each electrode through the stimulus maps shown at the far left. The stimulus field from each electrode recruits nerve fibers innervating the muscles shown. The muscles in the lightly shaded area are used in the lateral grasp, those in the darkly shaded area are used in the palmar grasp. The muscle force generates moments about the joints of the hand. The resulting moments and positions of each joint depend on the passive moments, gravity and external forces. The grasp output is defined as the moments and positions of each joint of the hand.

muscles. Each electrode may recruit nerve fibers to a number of different anatomically defined muscles. The number of nerve fibers recruited by an electrode increases as the stimulus level increases. The rate of increase depends on the distance between the electrode and nerve, and the threshold of each nerve fiber. As the recruited muscle contracts, tension is developed in the muscle tendon, generating a moment about each joint crossed by the tendon. The moment developed depends on the moment arm about each joint. The force developed by the muscle depends on the muscle length because of the length-tension property of muscle and because the relative position between the electrode and the nerve can change as the muscle contracts. Muscle length is affected not only by the angles of the joints of the hand but also, for the extrinsic muscles, the wrist and forearm angle and, for the finger extrinsics, the elbow angle. In addition, the muscle moment is affected by the stimulation delivered over time, primarily through the mechanism of fatigue and recovery. The moment and position of each joint depends on the active moment developed by each muscle, the passive moments about the joint, the force of gravity on the digit and any external loads and forces. The passive moments are a function of the joint angles. The orientation of gravity with respect to the hand depends on the joint angles of the entire upper

extremity. The moments and angles of each joint of the hand comprise the grasp output.

The factors which affect the grasp output have been divided into two categories. The first category contains those factors which are stable over time. These are the electrode-position dependent recruitment properties. The second category contains those factors which vary over time and those which are dependent on the task performed by the subject. These are known as the time and task dependent variables, specifically fatigue, size of the object being acquired and the extremity position. Figure I.3 highlights the relationship between these factors and the grasp output. All of these factors must be taken into account when developing a functional grasp pattern.

The goal of this project is to improve the grasp output by optimizing the stimulus map. The optimum stimulus map results in a grasp output where the influence of each variable on the grasp output is minimized. For those variables which are relatively constant over time, their influence can be compensated for directly if they can be measured. For those variables which are continuously changing, or whose state is unknown in the open loop system, their influence can be minimized by determining the appropriate parameters for synthesis of the stimulus map. Chapter III

Figure I.3. Influence of different factors on the grasp output. The lightly shaded area indicates the electrode recruitment properties. These properties are influenced by the relationship between the electrode and the nerve, the muscles that are recruited, and the positions of the joints of the hand and extremity. The time and task dependent variables are indicated by the darkly shaded areas. The extremity positions influence the orientation of gravity with respect to the hand, the passive moments and the recruitment properties (by changing the muscle length).

describes a method for synthesizing the stimulus map which compensates for the position dependent recruitment properties, known as the external moment grasp synthesis procedure (EMGSP). Chapter IV describes a method for determining the stimulus map which minimizes the influence of the time and task dependent variables on the grasp output. Chapter II describes a rule-based method for stimulus map synthesis, which is the method currently implemented clinically. The rule-based method and the EMGSP are compared by evaluating the grasp output patterns developed by each method. It is hypothesized that the EMGSP will produce better grasp patterns because it compensates for the electrode recruitment properties, whereas the rule based method compensates for only the stimulus threshold. In addition, it is hypothesized that the grasp output developed by the EMGSP can be further improved by minimizing the influence of the time and task dependent variables, which have not been addressed by previous methods of stimulus map synthesis. The specific hypotheses to be evaluated in this project are the following:

Hypothesis 1. The EMGSP can develop a stimulus map which compensates for the electrode-position dependent recruitment properties.

Hypothesis 2. The grasp outputs developed by the EMGSP will more closely match the desired grasp output when compared with the grasp

outputs developed by the rule-based method.

Hypothesis 3. The proper choice of the grasp template parameters can minimize the influence of the time and task dependent variables on the grasp output.

Hypothesis 4. The selection of electrodes according to particular input/output characteristics can reduce the grasp output errors.

II. RULE BASED METHOD FOR STIMULUS MAP SYNTHESIS

II.A. ABSTRACT

A functional neuromuscular stimulation system has been developed to provide grasp-release function in quadriplegic individuals. A single command input from the subject controls the stimulus levels to a number of electrodes, thus simultaneously activating several muscles. A method for synthesizing the command input to stimulus output relationship has been developed. The first step involves electrode profiling, which is a method for characterizing the output of an individual electrode/muscle combination. The electrodes are then grouped according to function and a set of rule based procedures is used to synthesize the basic grasp parameters. Results are presented demonstrating the output from lateral and palmar grasps developed by this method. The method has successfully resulted in grasping patterns that can be utilized functionally. Limitations of the method and future improvements are discussed.

II.B. INTRODUCTION

Spinal cord injury at the C5 or C6 level results in severe paralysis of the extremities. Functional neuromuscular stimulation (FNS) is a means of providing controlled hand function in these disabled individuals [36,37,38,39,41,42]. This paper presents a means of synthesizing two basic grasping modes, lateral prehension (key grip) and palmar prehension (three-jaw chuck grip) from activation of single muscles or muscle groups. Control of these grasping motions utilizes simultaneous proportional excitation of up to eight different muscles which act as synergists and antagonists. In order to simplify the control task that the paralyzed subject must perform, a single proportional command signal is used to simultaneously regulate the inputs to all of the muscle groups. The resultant grasp is a coordinated movement through which the subject obtains functional use of his paralyzed extremity. The method of synthesizing the relationship between the single command input and the stimulus output presented in this paper has been developed and modified over the past ten years. It is an integration of our clinical and scientific experience with upper extremity FNS systems.

II.C. METHODS

Subjects

Subjects in this program are individuals who are quadriplegic secondary to spinal cord injury with a resultant paralysis at the C5 or C6 level. Individuals with a C5 injury generally have voluntary control of shoulder motion and elbow flexion, but no other motor function below the elbow. Subjects with injury at C6 retain some voluntary control of wrist extension. Sensation in the hand is absent (C5) or minimal (C6) and if present, generally restricted to portions of the first two digits.

Electrodes

Subjects were implanted with coiled wire electrodes, introduced with a hypodermic needle, into the muscles to be stimulated. Up to sixteen muscles may be activated at any one time for functional use. These electrodes penetrated the skin at two sites (15mm x 15mm) on the distal forearm where they were covered with a silicon interface taped to the skin surface. The interface protected the electrodes and provides a simple electrical connection. In one subject, a receiver/stimulator was surgically implanted and epimysial electrodes were used for muscle activation [11,22,44].

The muscles implanted are the primary muscles for hand function and are shown in Table II.1. The intrinsic muscles of the fingers were excluded because precise electrode placement within these muscles is difficult and a considerable number of electrodes are required. Prior to implantation, supramaximal surface stimulation of the peripheral nerves proximal to the forearm was used to determine whether a muscle had an upper or lower motor neuron lesion [35]. While this technique does not allow determination of the degree of any partial denervation (lower motor neuron damage), it is a straightforward assessment which easily excluded muscles which were totally denervated.

System Description

The laboratory stimulation system, described in detail elsewhere [46], is used for grasp programming. The system provided independent regulation of up to sixteen channels of stimulus pulse width, amplitude, and period. In this study, amplitude and period were fixed and modulation was through pulse width only, although the techniques utilized are adaptable to modulation by other stimulus parameters as well. Stimulus parameters were transferred to a portable neuromuscular stimulation device to provide the individual with functional hand control. The system consisted of an

I. Finger Flexors

- A. Flexor Digitorum Profundus (FDP)
- B. Flexor Digitorum Superficialis (FDS)

II. Finger Extensors

- A. Extensor Digitorum Communis (EDC)
- B. Extensor Indicis Proprius (EIP)

III. Thumb Flexors

- A. Adductor Pollicis (ADP)
- B. Flexor Pollicis Brevis (FPB)
- C. Flexor Pollicis Longus (FPL)

IV. Thumb Extensors

- A. Extensor Pollicis Longus (EPL)
- B. Extensor Pollicis Brevis (EPB)

V. Thumb Abductors

- A. Abductor Pollicis Brevis (ABPB)
- B. Opponens Pollicis (OP)

Table II.1. Muscles implanted with percutaneous electrodes. The major headings indicate the functional muscle group.

electronics module, controller transducer and lead wires [3]. Each of the twenty-three subjects was supplied with a personal stimulation device.

Procedures for Grasp Synthesis

The procedure for synthesizing grasp involved determining the command input to stimulus output relationship, or grasp parameters. This involved four phases: electrode profiling, selection of grasp configuration, initial grasp parameter setup, and parameter modification.

Electrode Profiling. Electrode profiling was performed in order to rate the output characteristics of each electrode/muscle combination. These characteristics were important in the synthesis of the grasp parameters. They are defined as follows:

1) Threshold: The threshold is defined as the minimum stimulus necessary to elicit a muscle contraction. It is determined by increasing the pulse duration from 0 μ S (amplitude constant at 20mA, stimulus period constant at the minimal value that generates a fused response, generally 80ms) until a visible movement is seen in either the thumb or fingers as a result of muscle contraction. The muscle recruited at the lowest stimulus

level is considered the primary muscle. Muscles recruited above this point are referred to as secondary muscles. The threshold for movement of each digit is specified.

2) Primary Muscle Force: This is the maximum force of the primary muscle just below threshold activation of any secondary muscles.

3) Gain: Gain refers to the change in force per change in stimulus or change in position per change in stimulus for the primary muscle.

4) Selectivity: Selectivity is a measure of the isolation of the stimulus to a single anatomically defined muscle. It is defined as the percentage of total force recruited by the primary muscle prior to threshold for any secondary muscles.

5) Direction: This parameter specifies the direction of force application or the direction of movement. This parameter is primarily applicable to thumb flexion and abduction.

6) Length Dependency: This is the change in muscle output as a

function of wrist, forearm, and digit position changes during application of a constant level of stimulation.

The electrode profiling process involved observing the output of each electrode/muscle combination and rating them in categories 2 - 6 according to a scale of 0, 1, or 2 where 0 = nonfunctional, 1 = adequate, and 2 = excellent. These ratings were made by comparing the electrode/muscle combination output with that necessary for use in a functional grasp. For example, the primary muscle force for an electrode implanted in the extensor pollicis longus (used for thumb extension in the lateral grasp) was rated as follows: 0 = does not fully extend the thumb, 1 = fully extends the thumb prior to recruiting other muscles, 2 = fully extends the thumb with additional force resulting in a more stable thumb position. In some cases ratings may also be determined for the secondary muscle if it can be used functionally.

Electrodes were grouped into one of five functional divisions, as shown in Table II.1, according to the electrode profile. Generally several electrodes may be temporarily implanted into a muscle (muscle group) and selection of the electrodes for functional use must be made. The best electrode in each division was determined by comparing the electrode

profile ratings of the available electrodes in that group. An overall score for each electrode/muscle combination was obtained by multiplying the 0,1, or 2 rating from each parameter by a weighting value and summing each of these products. The weighting values were an indicator of the relative importance of each of the profile parameters to the function of a particular muscle group in palmar or lateral grasp and are shown in Table II.2. The overall score provided a basis of comparison between electrodes in the same functional group. The weighting parameters were determined empirically by experience in synthesizing coordinated movements of the hand. Examination of the weightings revealed some important differences. For example, in palmar prehension modest recruitment gain of finger flexors and extensors was important in order to provide graded pinch force. In contrast, little weight was given to the gain factor for the finger flexors and extensors in lateral prehension since the primary objective was only to have a stable base through which the thumb force was transmitted.

Grasp Configurations

Two grasp configurations have been selected, lateral prehension (or key grip) and palmar prehension (or three jaw chuck pinch) and release. The selection of these grasp configurations is based on the studies of Keller

Lateral Grasp

<u>Weightings</u>	<u>MF</u>	<u>G</u>	<u>SL</u>	<u>Dir</u>	<u>LD</u>
Thumb Extensor	5	8	10	3	5
Finger Extensor	5	1	10	0	5
Finger Flexor	7	0	5	0	5
Thumb Flexor	8	8	5	5	6

Palmar Grasp

<u>Weightings</u>	<u>MF</u>	<u>G</u>	<u>SL</u>	<u>Dir</u>	<u>LD</u>
Thumb Abductor	4	0	10	10	8
Finger Extensor	8	8	10	0	5
Finger Flexor	8	8	8	0	5

Table II.2. Weightings for electrode parameters for each muscle group. A zero weighting indicates that the parameter is not important to a particular muscle group and a ten weighting indicates primary importance. MF = maximum force, G = gain, SL = selectivity, Dir = direction and LD = length dependence.

et al [23], who found that normals used these two grasps for a majority of the tasks involving acquiring common objects. For pick-up tasks, normals used palmar and lateral prehension to grasp 34% and 58% of the objects presented, respectively, and in holding objects for use the respective frequencies were 64% and 34%.

Synthesis of grasp was achieved by tuning the stimulus parameters to elicit the desired positions and contact forces of the digits. The desired relationship between the single input command control signal and the position and force output of the digits was referred to as the grasp template. The command signal ranges from 0 to 100%, where 0% corresponds to an open hand and 100% corresponds to a fully closed hand exerting maximum grasp force.

Lateral Grasp. The grasp template, or desired grasp output, for the lateral grasp is shown in Figure II.1. The fingers initially were extended and the thumb fully extended. Within the next 20% of the command range the fingers were flexed linearly until they reached full flexion. Thumb position changed linearly from full extension to contact with the index finger over the command range from 20% to 50%. Over the last half of the command range the thumb applied force onto the index finger and this force increased linearly as the command increased. This grasp is used for picking up small

LATERAL GRASP

Figure II.1. Desired lateral grasp template. Finger position ramps linearly from full extension to full flexion over the first 20% of the command range. Thumb position begins in full extension and is decreased linearly from 20 to 50% of the command range. Over the last half of the command range, the thumb pinch force increases linearly in the direction of flexion.

objects, writing and eating.

Developing the lateral grasp required four functional components: thumb extension, thumb flexion, finger extension and finger flexion. The parameters for the lateral grasp were then determined for each functional group as described below.

1) Finger Extension. The stimulus to the finger extensor was linearly decreased from the maximum stimulation prior to recruitment of fibers from other muscle groups (referred to as spillover) to a subthreshold stimulus in the first 10% of the command range. This initial finger extension, coupled with thumb extension, provided full extension of all joints at the 0% command level. Subjects have found this to be a useful position for hand placement around objects.

2) Finger Flexion. The preferred muscle for finger flexion in the lateral grasp was the FDP because it flexes all three finger joints. The fingers were used in this grasp to form a base against which the thumb applies pinch force. The stimulus to the finger flexors was increased linearly

from subthreshold to maximum stimulus prior to spillover over the command range from 10 to 20%. The stimulus was then maintained at a constant value over the remaining 80% of the command range. A single electrode rarely recruited all fingers at an equal force level. As a result, more than one electrode must usually be used for finger flexion. As many electrodes as are necessary were recruited until flexion of all fingers occurs. Each added electrode follows the same pattern as above. Isolation of the stimulus to the finger flexors was critical, and spillover from other muscle groups has not been found acceptable.

3) Thumb Extension. The thumb extensor was recruited initially at the highest level of stimulation prior to spillover to muscles other than the EPL or EPB. This level is maintained to 20% of the command range, where the stimulus is decreased linearly to subthreshold at 60% of the command range. Spillover from a thumb extensor to a finger extensor can be used over the range from 0 to 10% command, where finger extension was desired.

4) Thumb Flexion. The thumb flexors were recruited linearly from subthreshold at 50% of the command range to maximum at 100% of the

command range. The region from 50 to 60% of the command provided cocontraction of both the thumb flexor and thumb extensor. This resulted in a smooth transition from thumb positioning to thumb flexion. Spillover from the thumb flexor to the finger flexor was acceptable because the fingers were already in full flexion.

The preferred muscles for thumb flexion are the ADP and FPB (the ADP provides a component of both flexion and adduction). The FPL, although a strong thumb flexor, primarily flexed the thumb interphalangeal (IP) joint, which was an undesirable action in lateral pinch. Fusion of the IP joint permitted the FPL to be used in lateral pinch, and under these conditions it is an excellent muscle [22].

Palmar Grasp. The grasp template for the palmar grasp is shown in Figure II.2. This grasp is used for picking up larger objects such as a cup or a book. In this grasp, the thumb position remained constantly in opposition throughout the command range. Finger position changed linearly from full extension to full flexion as the command changes from 0% to 60%. From 60% to 100% the force of the fingers on the thumb was increased linearly. The palmar grasp used three functional groups: thumb

PALMAR GRASP

Figure II.2. Desired Palmar grasp template. Finger position ramps linearly from full extension to contact with the thumb over the first 60% of the command range, where finger contact force begins to increase linearly up to 100% of the command range. Thumb position is maintained in constant abduction throughout.

abduction, finger extension and finger flexion.

1) Thumb Abduction. The thumb abductor was maintained at a constant stimulus level throughout the command range. In some cases the greatest web space opening was achieved through contracting more than one muscle.

2) Finger Extension. The finger extensors initially were recruited at the maximum stimulus level prior to spillover. The stimulus was decreased linearly as the command increases from 0 to 55%.

3) Finger Flexion. The finger flexors were increased linearly from subthreshold to maximum stimulus level prior to spillover from 45 to 100% of the command range. This allowed a region of cocontraction from 45 to 55% to smooth the transition from extension to flexion. The FDS was the more desirable finger flexor for the palmar grasp because it enables the fingers to close around larger objects with their palmar portion. The FDP flexes the distal interphalangeal (DIP) joints, often excluding the object from the grasp or providing insufficient closure force on the object. The finger intrinsics have not been used in our studies, as described in the discussion.

Tuning of Input-Output Relationship

The profiling process provides a means of establishing grasp parameters for coordinated hand movement. The threshold and maximum stimulus values were input parameters to the procedures described above. These procedures provide for linear change in the stimulus from threshold to maximum over the appropriate percentage of the command range and result in the basic grasp parameters. The resulting output generally will not be linear because of the nonlinear recruitment properties of each electrode/muscle combination. The output can be modified by alteration of the command - stimulus relationship to obtain the desired relationship of position or force to command.

The relationship between stimulus input and force or position output for an individual electrode/muscle combination is nonlinear [5]. This nonlinear relationship can be corrected by inverting the command vs. normalized force relationship. Therefore the method described above, which utilizes a command to stimulus relationship in which the stimulus is linearly increased from subthreshold to maximum stimulus, can be modified by substitution of a piecewise linear stimulus to command relationship which will yield a more linear grasp output. This method was tested by obtaining

the recruitment curves (force/position vs. stimulus pulse width) for electrodes in the thumb at six stimulus levels. A single value on the recruitment curve was determined by stimulating the muscle for three seconds at a constant pulse width and the force or position output was averaged over the last 0.5 seconds. The recruitment curve was normalized to the force or position value obtained at maximum stimulation (200uS pulse width). This curve was inverted to generate a command vs. pulse width relationship. The experiment was repeated by obtaining force/position output at 0,20,40,60,80 and 100% of the modified command relationship. Comparison could be made between the actual command vs. force/position relationship with the desired linear command vs. force/position relationship. The error between the actual and desired relationship was determined by calculating the percent deviation of each of the six points from the desired line.

II.D. RESULTS

Twenty-three subjects have been implemented with either a lateral (6), palmar (1), or both (15) types of grasp functions. Table II.3 shows a summary of the muscles implanted for functional use in these subjects. Seven muscle groups were identified as important for functional use and

	<u>EPL/EPB</u>	<u>ADP</u>	<u>ABPB</u>	<u>FPL</u>	<u>EDC</u>	<u>FDS</u>	<u>FDP</u>
Denervated	1	0	0	2	2	0	2
Implanted	22	22	23	12	20	23	21
Used in Lateral Grasp	19	20	8	8	8	16	14
Used in Palmar Grasp	8	2	17	1	14	15	6

Table II.3. Number of muscles implanted and utilized functionally for 23 subjects.

only 4.5% (7/154) were found to be denervated (lower motor neuron lesion) and therefore unusable functionally. Nearly all of the subjects had electrodes implanted in each of the seven muscle groups except the FPL which is usually only used functionally with a fused IP joint, a procedure that has been performed with five subjects. The most commonly used muscles for the lateral grasp were the ADP, EPL/EPB, FDS and FDP, respectively. For the palmar grasp, the most commonly used muscles were the ABPB/OP, FDS, EDC and EPL/EPB.

Electrode Profiling

Electrode profiling provided a means for qualitatively assessing the relative merits of a given electrode and its potential value in a grasp pattern. Figure II.3 shows an example of the electrode profiling comparison for three electrodes implanted in the thumb extensor for one subject. All three electrodes have generated sufficient strength, but they were well differentiated by their other characteristics. Electrode #1 has poor selectivity, gain, and length dependence. Electrode #3 would be chosen over electrode #2 because it has a higher gain and length dependence rating.

Complete electrode profiles have been performed on 160 different

Electrode Profile

Subject: GHP
Muscle Group: Thumb Extensor

Figure II.3. Electrode profiling results for three electrodes implanted in the thumb extensor group. Electrode #3 would be chosen because of its higher ratings in all categories. PF = primary muscle force, Sel. = selectivity, LD = length dependency.

intramuscular electrodes and seven epimysial electrodes in ten subjects. The profiles have been a successful method of determining the best electrodes in each functional group. They indicate the need for implantation of new electrodes by exposing deficiencies in the output properties of a particular muscle group. They also provide a data base of electrode characteristics. Of the 160 intramuscular electrodes characterized, 14% exhibited no spillover from one muscle group to another. The predominant spillover patterns that have been observed are ADP to first dorsal interosseous (1DI) (89% of all ADP electrodes also recruit the 1DI prior to the maximum stimulus level of 200uS), EPL/EPB to EIP (50%), EDC to EPL/EPB (65%) and ABPB to FDS (58%). Although spillover is common, it is not necessarily the reason for rejecting an electrode. This depends upon the muscle group and the muscle which is secondarily recruited. For example, the latter two spillover patterns can be utilized functionally to take advantage of the spillover.

Grasp Synthesis

The automated procedure of grasp synthesis provides an initial approximation to the desired grasp template. The threshold and maximum stimulus values from the electrode profile are used to determine the basic

grasp parameters according preset procedures for each grasp.

Lateral Prehension. The grasp parameters and grasp output for lateral prehension developed for one subject (SHA) are shown in Figure II.4a. These represent the command vs. pulse width relationship for each electrode/muscle combination used in the grasp. Figure II.4b shows a photographic sequence of the hand movement at command level inputs of 0, 40, 60, and 100%. Four finger flexor electrodes were used to obtain strong flexion of all fingers. Two of the four electrodes recruited only the index finger and the other two recruited the long, ring and small fingers. Generally, two electrodes would be required for finger flexion, but strong finger flexion was necessary to overcome high passive forces in this subject's finger joints. Two thumb muscles, both recruiting the ADP, were used to obtain maximum thumb flexion. The thumb extensor electrode also recruited finger extensors at pulse widths above 100uS and this spillover was utilized for finger extension over the initial 20% of the command range.

Palmar Prehension. Figure II.5a shows the grasp parameters and grasp output for the palmar grasp for subject SHA. Figure II.5b shows the subject's hand at command levels of 0, 40, 60, and 100%. All of the subject's available finger flexor electrodes were incorporated into this grasp

Figure 11.4a. Actual lateral grasp for subject SHA. The top four curves show the force and position output of the thumb and fingers. The bottom five curves show the grasp stimulus parameters developed. Eight electrodes were used in this grasp. The thumb contact force is divided into its magnitude (mag.) and direction (dir.).

Figure 11.4b. Photographs of the lateral grasp for subject SHA at 0, 40, 60, and 100% of the command range. These percentages correspond to the independent axis in Figure 11.4a.

Figure II.5a. Actual palmar grasp. The top three curves show the force and position output of the thumb and fingers. The bottom five curves show the grasp stimulus parameters developed using eight electrodes. The FPL was added to increase the total pinch force at higher command ranges.

Figure II.5b. Photographs of the palmar grasp for subject SHA at 0, 40, 60, and 100% of the command range.

in an effort to obtain maximum grasping force. Thumb flexion was added over the last 20% of the command range by stimulation of the FPL to increase pinch force. A large degree of cocontraction was used between the EDC and FDS to smooth out high gain recruitment in the finger flexor.

These modifications indicate some of the changes that can be made as a result of functional observations of the subject using the basic grasp.

Linearization of Force and Position. The automated procedure developed to date provides an initial approximation to the final desired parameters. Further refinement is obtained by linearizing the input-output relationship. The linearization experiments were conducted with three subjects using a thumb flexor or extensor muscle [10]. It was found that a command versus pulse width relationship could be developed which would provide a linear command versus force relationship. Figure II.6 shows the linearization procedure performed with one of the three subjects. Initially the basic grasp parameters are a linear relationship between command and pulse width resulting in a nonlinear force output as shown in the top two graphs. This nonlinear relationship was then inverted to create the command versus pulse width relationship, where the percent of

Initial Grasp Parameters

Modified Grasp Parameters

Figure II.6. Force linearization procedure. The top two plots show the grasp parameters that would be developed to produce thumb flexion and the actual command vs. force output. The bottom two plots show the modified grasp parameters to account for the nonlinearities in the force recruitment. The actual output as a result of this modification is nearly linear (maximum deviation from desired line is 6% of the total force).

normalized force at a given pulse width corresponds to the command percent at that pulse width. The new command versus force relationship was then tested at 20% command increments as shown in the bottom two graphs of Figure II.6. The resulting force output is within $\pm 10\%$ of the desired 45 degree line.

The linearization technique for force recruitment was tested with three subjects and produced an input-output relationship that was more linear than the original recruitment. In two out of the three subjects the resulting relationship had all data points within $\pm 10\%$ of the desired line and therefore successfully compensated for the nonlinear recruitment within the expected variation due to fatigue (10%). In the third subject, 4/6 points were within $\pm 10\%$ and the linearity was improved by the technique.

In similar experiments performed using thumb position recruitment, the thumb position was within $\pm 10\%$ for all points (12/12) for two subjects and within $\pm 10\%$ for 5/6 points for the third subject. These results indicate that both force and position can be successfully linearized using this procedure.

Functional Capabilities

The complete description of functional return derived by patients who have been provided with FNS restored grasps is beyond the scope of this paper. However, it is noteworthy to report that each of the 23 subjects reported in this study were fitted with functional motor prosthetic systems for restoration of grasp. Most subjects used shoulder motion to generate the proportional command and elicit lock/unlock signals. All subjects have demonstrated the ability to control hand movement and integrate the movements into their remaining voluntary control. They are able to perform activities of daily living with versatility, moving from manipulation of one type of object to another, and select the grasp pattern which is appropriate for the task to be performed. Subjects have used the FNS neural prosthesis as outpatients for as long as nine years, continuing to derive functional benefit over the entire period [42].

The functional capabilities of subjects with and without their FNS neural prosthesis have been compared by testing the subject's ability to perform eight specific tasks. These tasks are: lifting a book, using the telephone, writing, using a toothbrush, picking up a glass and a mug, picking up finger food and using a utensil for eating. At least 20 subjects have been in tested with each task. Subjects were allowed to use both

hands and splinting as necessary, but no attendant assistance or adaptations to the objects were allowed. The number of subjects that could successfully complete each task was at least doubled for every task when the subject used their FNS neural prosthesis. Subjects with a C5 level injury showed greater improvement than those with a C6 level injury. This is primarily due to the greater ability of the C6 level subjects to perform more tasks prior to receiving their FNS system. Further tests are presently ongoing to measure the functional ability derived from this neural prosthesis.

II.E. DISCUSSION

The loss of motor and sensory function in the hands of high level quadriplegic individuals has devastating consequences that can result in the loss of independence. Restoration of functional control to the upper extremities of these individuals is an integral goal of a comprehensive rehabilitation program. FNS of the paralyzed muscles is one approach that can be used to restore lost function. Synthesis of movement is one of many aspects in the process of providing FNS control for functional restoration.

The synthesis of coordinated functional grasp-release patterns must provide reliable and repeatable movement and be achieved using

straightforward methodology. The process which we describe in this paper accomplishes these objectives. The method provides a means of identifying the unique input-output characteristics of a given electrode or electrode type activating a particular muscle group, and weighing its relative features as related to the desired function. Thus, the procedure is practical in that it recognizes and contrasts limitations in muscle-nerve activation that may be expected to be encountered with all described electrode types. Furthermore, the procedures provide a framework for future enhancement and automation of the grasp synthesis process, which may be expected to increase ease and reduce variability in the quality of grasps.

The procedure for grasp synthesis that has been developed is independent of the type of electrode (e.g. surface, indwelling) used or the mechanism of activation (e.g. reflexive or direct) of the peripheral nerve. However, the results clearly indicate a need for selective and graded activation of the various individual muscle groups which can be achieved repeatably over time. In contrast to others, our experience is that these objectives cannot be met by electrodes placed on the skin surface [32,43]. These electrodes tend to be very sensitive to placement, generally lack sufficient selectivity except for quite gross activation, and have inherent length dependent activation [29]. We believe that these electrodes are

unsuitable for obtaining the precisely regulated control necessary for functional use of the hand. Thus, the orientation of this paper is toward indwelling electrodes, of which the percutaneous intramuscular is a minimally invasive type. This electrode demonstrates the range of various qualities that might be encountered, depending upon its precise placement at installation.

The synthesis of functional grasping patterns of the hand from a subset of the normal number of muscles used in voluntary movement is a compromise between precise digital control of each joint and the number of muscles that can practically be activated and regulated within basic clinical constraints of both installation and maintenance. To this end, we have attempted to limit the number of active patterns of movement to those which are primarily used in activities of daily living. The examination of basic grasp patterns used in normal voluntary activity [23], as well as experience of reconstructive surgery of the hand in quadriplegia [9], has shown that providing the versatility of most complex grasping patterns is beyond the scope of initial clinical implementations. Since the vast majority of tasks can be accomplished by two grasp patterns, lateral and palmar prehension, our orientation has been synthesis of those movements. Further limitations have been constrained by technical and surgical

considerations to limit the number of muscle groups activated to eight or fewer. This number is consistent with the limitations of both percutaneous and surgical installation as well as servicing in the event of lead or electrode failure. Thus, our approach has excluded usage of the finger intrinsic muscles, although their role is recognized to be important in normal hand movement [28].

The procedure which is used to synthesize grasp must consider the variations which are presented by the hands of individual patients. Such variations include limitations on the range of movement, joint laxity and denervation of primary muscle groups. More specifically we have found: joint/ligament/muscle contractures which may limit the range of motion of the joint or require high forces, particularly at the extremes of the range of motion; joint laxity which may result in collapse of the joint and transmission of an insufficient amount of force across the joint; total denervation which may limit the muscles that are available for functional excitation or partial denervation which may reduce the strength of the contraction. For example, claw hand deformity, a contracture which results from an ulnar minus hand, limits the usefulness of the subject's hand in palmar grasp because the EDC does not generate a sufficient moment about the distal finger joints to achieve full extension. Contractures of the web space to the

thumb limit the size of objects that may be acquired in either grasp. These factors, coupled with the precise recruitment properties that are not known or predictable a priori, require an interactive process for movement synthesis. The procedure which we have used incorporates these factors in establishing functional movement.

Handa et al. [12] have used EMG recordings of normal muscles to determine the stimulation parameters. The EMG recordings were made through electrodes implanted in each of the muscles in the thumb and fingers. The recordings were made as the hand of a non-paralyzed subject performed a particular type of grasp function. The relative EMG signals were then rectified and filtered and used to develop the relative stimulus levels for each electrode. This was done by approximating the EMG signals as a trapezoidal envelope. A similar method was used with circumduction of the thumb, although in this demonstration movement was constrained more by the anatomical limit to the range of motion rather than the magnitude of activation of the muscles. While this method may provide useful information on normal hand physiology and biomechanics, its applicability for determination of grasp parameters is unclear. This is because the paralyzed forearm and hand musculature and joints may be very different from a normal forearm and hand, as described above. As a

result, the EMG of normal muscles may not approximate the stimulus that must be delivered to a paralyzed muscle to produce the same muscle output, even if the same electrode is used for both recording and stimulating. This results from the fact that the EMG signal is recorded from fibers of different sizes and distances from the electrode. The stimulus will preferentially activate the larger fibers because they have a lower threshold for stimulation. As a result, the recruitment threshold and regions of high and low gain may not have any correlation to the measured EMG signal. EMG's, of course, could not be measured functionally from a paralyzed hand so measurements from electrodes in normal subjects have to be used. In particular, the electrode placement is crucial in determining the resulting force output of the muscle. Electrodes in paralyzed muscle may recruit only part of the fibers of a muscle or they may recruit fibers of a number of muscles. For these reasons, the stimulus required to produce a given movement in paralyzed muscles cannot be approximated by the EMG recorded from normal muscles during the same movement. The grasp produced as a result of this method may be no better, or even worse, than grasps produced through a purely iterative and qualitative process.

Surgical alterations can be performed to enhance the performance

of the FNS grasping system. These procedures have been reported previously [22] and include: tendon transfers, tenodesis of the long tendons of the fingers, Zancolli-lasso intrinsicplasty and fusion of the IP joint of the thumb. Tendon transfers are used to replace function lost due to lower motor neuron lesion of muscles necessary for grasping functions. An unused upper motor neuron lesioned muscle is transferred to the tendon of a lower motor neuron lesioned muscle, allowing function to be restored through stimulation of the transferred muscle. Synchronous motion of the fingers can be achieved through side-to-side anastomosis of the tendons of the FDP, the FDS and the EDC muscles. This allows a single electrode to move all four fingers as a unit. A surgical solution to the inability to utilize the finger intrinsic muscles is a Zancolli-lasso intrinsicplasty in which the FDS insertion is moved to the intrinsic insertion point. Thumb IP fusion provides joint stability and allows the FPL muscle to be used as an active thumb flexor. These surgical solutions reduce the actuators (muscles) and reduce the mechanical complexity (degrees of freedom) that are necessary to control hand grasp.

The optimal grasp template for each type of grasp is presently unknown. The grasp templates currently used for the palmar and lateral grasp were developed from observations of normal function and modified

through experience with subjects performing grasping functions. However, the process described in this paper is independent of the grasp template and this allows modification of the template as further information becomes available regarding the optimum grasp configuration.

The method of grasp synthesis which we have presented is a qualitative procedure that can easily be adapted to incorporate more quantitative information. Each of the profile characteristics, for example, can be determined by measuring the force and/or position output of each electrode as a function of stimulus level and joint position. This would allow the profile ratings to be replaced with numerical values. For example, the maximum force parameter can be determined by measuring the force output with a pinch meter. Further automation to the entire process can be achieved by measuring the recruitment curves and using them as the basis for the grasp parameters. An example of this type of process presently utilized was shown in Figure II.6, where the recruitment curve was inverted to produce a linear force vs. position output. These improvements in the quantitative nature of the process will mean fewer iterations on the basic grasp parameters and are appropriate for automation using an intelligent computerized system.

III. COMPENSATION FOR ELECTRODE RECRUITMENT PROPERTIES

III.A. ABSTRACT

Functional neuromuscular stimulation (FNS) has been used in open loop upper extremity neuroprostheses to provide grasp and release for quadriplegic individuals. A principle issue in an open loop implementation of the neuroprosthesis is the synthesis of the stimulus map, which is the relationship between the input control signal and the output stimulus applied to each electrode. The goal of this project was to develop a method of stimulus map synthesis which compensates for the influence of the electrode-position dependent recruitment properties on the grasp output, and which can be performed using automated procedures. A method called the external moment grasp synthesis procedure (EMGSP) has been developed which meets these criteria. The EMGSP uses an external moment model of the hand which describes the interaction between the active moments produced by electrical stimulation, the passive joint moments, and the total joint moment and angle. The EMGSP was used to develop the stimulus map for three paralyzed subjects, and in all cases the EMGSP-generated grasp had lower errors than grasp patterns developed using the previously implemented rule-based method of stimulus map

synthesis. The difference between the desired maximum force and position and the actual maximum force and position was minimized within three iterations. The EMGSP was successfully implemented by computer and was able to compensate for the effects of the electrode recruitment properties on the grasp pinch force.

III.B. INTRODUCTION

Functional neuromuscular stimulation (FNS) has been used to provide grasp and release for individuals with a spinal cord injury at the C5/C6 level [1,13,27,32,42,43]. Muscles which are paralyzed due to the spinal cord injury are implanted with electrodes for delivery of a graded electrical stimulus for activation and control [5]. The resultant movement is controlled by remaining voluntary movements from the quadriplegic individual. A proportional command-control signal is used to control grasp opening and closing; and logic signals are used to turn the system on and off, change grasp patterns and provide lock and unlock signals [19]. A controller/stimulator is responsible for converting the proportional command signal to the appropriate stimulus levels for each electrode so that the desired grasp pattern is achieved [3]. Two grasp patterns are developed, lateral pinch and palmar prehension [41]. In the lateral pinch, the fingers are flexed to form a base for the thumb. In palmar prehension, the thumb is posted in opposition and the fingers flex against it.

The desired grasp output, or grasp template, describes the joint moments and positions necessary to accomplish particular tasks [24]. Therefore it is important that the stimulus map be developed to minimize the error between the grasp template and the actual grasp movement. The

process through which coordinated movement of the electrically activated muscles is established is known as movement synthesis. The process of movement synthesis establishes the relationship between the proportional control signal and the stimulus level to each of the electrodes, known as the stimulus map. This map must be customized for each subject because the output of each electrode varies from subject to subject [25,41]. Several factors influence the electrically elicited grasp output, resulting in differences between the desired grasp output and the output of the neuroprosthesis. These factors can be placed into three categories according to the manner in which they affect the grasp output, as shown in Table III.1. They are the controlled variables, the electrode-position dependent recruitment properties and the time and task dependent variables. The controlled variables are the stimulus pulse width, amplitude and frequency. The second category is the electrode-position dependent recruitment properties of each electrode (threshold, gain and length dependency) [25]. These properties are dominated by the position of the electrode relative to the muscle innervation. A large change in these characteristics probably indicates a broken or dislodged electrode. In addition to electrode position, the electrode recruitment properties are also dependent on the state of the neuromuscular system, including factors such as fatigue and potentiation.

Table III.1.1. Variables that Affect the Grasp Output

<u>Controlled Variables</u>	
1.	Stimulus Amplitude
2.	Stimulus Pulse Width
3.	Stimulus Period
<u>Electrode-Position Dependent Recruitment Properties</u>	
1.	Threshold for force recruitment
2.	Nonlinear force output as a function of stimulus input
3.	Length-Tension property of active muscle
4.	Changes in the electrode/nerve geometry with muscle contraction
<u>Time and Task Dependent Variables</u>	
1.	Fatigue
2.	Orientation of upper extremity
3.	Size and shape of object

These factors are included in the third category, known as the time and task dependent variables. These variables may change whenever the subject attempts to grasp an object. They are fatigue¹, object size and extremity position. Extremity position affects the grasp output through two mechanisms: by changing the length of the stimulated muscles and by changing the relative orientation of gravity with respect to the hand. The goal of stimulus map synthesis is to utilize the controlled variables to produce a grasp output that is minimally affected by the position dependent recruitment properties and the time and task dependent variables. The following section reviews the current methods for stimulus map synthesis, demonstrating that they do not address this goal.

Existing Methods for Stimulus Map Synthesis.

Open loop neuroprosthetic systems have been described by Handa and Hoshimiya [13,15,16], Kawamura [1], Kralj and Vodovnik [27], Nathan

¹ "Fatigue" is used throughout this paper to describe the electrode recruitment properties which are dependent on the condition of the neuromuscular system, of which muscle fatigue is the primary component. Other components include potentiation and variations due to the fact that this is a dynamic living system with continuously varying conditions. At present, we know of no way to separate the effects of each component.

[33] and Peckham et al. [22,37,38,41,42],. Synthesis of the stimulus map generally involves determining minimum and maximum stimulus levels for each electrode and linearly modulating the stimulus between these levels. The CWRU/VA system [22,37,38,41,42] employs a rule-based procedure to synthesize the grasp stimulus map [24], which was described in Chapter II. In the rule-based procedure, threshold values are determined for each electrode and used to set minimum and maximum stimulus levels. Grasp templates are developed which specify the relationship between the proportional command input and the minimum and maximum stimulus levels. The templates are organized by functional muscle groups and are determined from the desired grasp patterns (lateral and palmar). The stimulus level as a function of the command input varies linearly between the minimum and maximum stimulus levels. Modification to the stimulus map is performed by the investigator after qualitative observation of the grasp output.

The neuroprosthetic system implemented by Handa, et al. [13,15,16], uses a similar procedure except that the templates are organized by individual muscles rather than by muscle groups. EMG analysis of normal muscle during grasping movements was used to develop these templates. The minimum and maximum stimulus levels are adjusted for each muscle

until the desired movement is achieved. The stimulus amplitude is varied linearly between the two levels. In some cases the subjects are allowed some control of the maximum stimulus levels. Handa has indicated that this technique of grasp synthesis requires many iterations to produce a final acceptable grasp and requires several hours of programming with the subject [14].

Other open loop upper extremity systems described by Kawamura, et al.[1], Nathan [33], and Kralj and Vodovnik [27], have been presented in the literature, but their methods for synthesis of the grasp stimulus map have not been reported.

The grasp output developed by the methods described above is affected by the position dependent recruitment properties of each electrode and by the time and task dependent variables. No procedure exists for minimizing the influence of these variables on the grasp output, with the exception of the stimulus threshold. Therefore, the objective of this project was to develop a method for determining the optimum grasp stimulus map for the open loop neuroprosthesis. The optimum grasp stimulus map is defined as the grasp stimulus map for which the resulting grasp output most closely matches the desired grasp output in the presence of the electrode recruitment properties and the time and task dependent variables.

This paper describes an automated method of grasp synthesis, known as the external moment grasp synthesis procedure (EMGSP), which compensates for the influence of the electrode-position dependent recruitment properties on the grasp output. A method for minimizing the influence of the time and task dependent variables on the grasp output is described in Chapter IV.

The specific goals of this chapter are: 1) to demonstrate that the EMGSP can be implemented experimentally, 2) to compare the grasp output developed by the EMGSP with the grasp output developed by the rule based method and 3) to evaluate the ability of the EMGSP to compensate for the position dependent electrode recruitment properties.

III.C. METHODS

Compensation for the Electrode-Position Dependent Recruitment Properties

The stimulus threshold, gain and length dependency of each electrode are primarily determined by the electrode position within the muscle. These characteristics, referred to as the electrode-position dependent recruitment properties, are therefore stable as long as the electrode is not dislodged. These properties can be measured as a function of the input stimulus level and joint angle. Compensation for these

properties can be achieved by determining the stimulus levels applied to each electrode which will yield the desired moments and joint angles at a series of discrete points in the command range. This is accomplished using a method called the external moment grasp synthesis procedure (EMGSP), which is shown in Figure III.1. The inputs of the EMGSP are the joint moment recruitment curves (JMRC), the passive moment and the grasp template. The JMRCs contain the moment output as a function of stimulus pulse width and joint angle for each electrode. The grasp template specifies the desired moments and positions of each joint as a function of the input command level. The external moment model (EMM) uses the JMRCs for each electrode, the passive moment (including tendon, ligament, soft tissue and gravity moments), and the grasp template to synthesize the stimulus map. The grasp output can be measured and compared with the grasp template. If there are differences, the grasp modification procedure is used to alter the stimulus map to reduce those differences. The EMM and the grasp modification procedure are described in the following paragraphs. The entire procedure is performed automatically by computer.

External Moment Model. The EMM describes the interaction between the active moments produced by electrical stimulation, the passive joint moments, and the total joint position and moment output. It is called the

Figure III.1. The method of grasp stimulus map synthesis presented in the paper, called the external moment grasp synthesis procedure. The inputs to the model are the joint moment recruitment curves (JMRC) of each electrode, the passive moments and the grasp template. The output of the model is the stimulus map for each electrode. The measured grasp output is used as the input to the grasp modification procedure.

external moment model (EMM) because it incorporates only the externally measurable active and passive moments about the joints of the hand, with no assumptions regarding the forces developed on each tendon and ligament. It assumes that the active moments produced by each electrode/muscle combination can be summed with the passive moments to predict the total moment. Joint angle is predicted as the angle at which the sum of moments is zero.

The objective of the EMM is to find the combination of stimulus levels to each electrode which minimize the difference between the desired grasp output and the predicted grasp output, i.e. minimize the grasp error. This objective can be stated as:

$$(1) \quad \Phi = G^T \times E$$

where:

Φ = Objective function to be minimized

E = Vector of grasp error terms

G = Vector of grasp error term gains

The error vector terms (E) are the grasp error values for each moment components of the grasp output, e.g. thumb CMC extension/flexion moment, thumb CMC abduction/adduction moment, index finger MP extension/flexion moment, etc.. The gain vector (G) indicates the

relative importance of each moment component to the overall grasp output.

Each error term is calculated as the difference between the desired grasp output and the predicted grasp output for each moment component.

The predicted grasp output is the sum of the passive moment, and the active moments produced by each electrode. This is stated in the general case for a single moment component as follows:

(2)

$$M_{Pred} = M_{Pas}(\Theta_1, \dots, \Theta_n) + M_{E1}(PW, \Theta_1, \dots, \Theta_n) + \dots + M_{En}(PW, \Theta_1, \dots, \Theta_n)$$

where:

Θ_n = Joint angle component n

PW = Stimulus pulse width

M_{Pred} = Predicted total joint moment

M_{Pas} = Passive joint moment

M_{En} = Active joint moment produced by electrode n

The passive moment is a function of the angles of each joint. The active moment produced by each electrode is a function of the angles of each joint and the stimulus pulse width. The relationship between joint angle, pulse width and active joint moment for each electrode is contained

in the JMRC. The joint angles contained in the grasp template are used to determine the appropriate passive and active moments for each point along the command range.

The stimulus values which minimize the value of the objective function (equation 1) can be found by searching all combinations of pulse width values for each electrode. However, the number of combinations increases by 200^n , where n is the number of electrodes. A solution can be obtained much faster by taking advantage of the segmentally linear relationship of each JMRC. Each set of linear segments can be solved as a linear system using singular value decomposition (SVD) [8,20]. The SVD method is used because the system may be over or under determined, depending on the number of electrodes used in the grasp.

The solution for a single command signal - pulse width pair is achieved by searching through the possible combinations of linear segments until a valid solution is found. The least squares solution is found at 21 points along the grasp input/output relationship (5% increments of command). The resulting output of the EMM is a set of 21 pulse width (PW) values for each electrode. The pulse widths are linearly interpolated for command values between the 5% steps.

The EMM initially seeks solutions which have the least amount of

cocontraction and have a predicted grasp error below a previously specified limit. If no solution can be found, then the entire field of possible solutions is searched in order of increasing cocontraction, which is defined as the sum of the absolute value of the active and passive moments. Therefore, the model has a preference for solutions with low levels of cocontraction. In certain cases, however, it may be advantageous to increase the stiffness of the hand, so a cocontraction constraint can be added to require the solution to be above a certain level of cocontraction. The cocontraction is included in the EMM by adding a cocontraction error term to the error vector (equation 1). The cocontraction error term is calculated as follows:

$$(3) \quad E_{CC} = CC - \{ |M_{Pas}| + |M_{E1}| + \dots + |M_{En}| \}$$

Where:

E_{CC} = Cocontraction error term

CC = Cocontraction level

$|M_{Pas}|$ = Absolute value of the passive moment

$|M_{En}|$ = Absolute value of the active moment developed by
electrode n

The specific moments analyzed by the EMM as implemented in this project were: 1) flexion/extension moment about the thumb

carpometacarpal (CMC) joint, 2) abduction/adduction moment about the thumb CMC joint and 3) flexion/extension moment about the index finger metacarpophalangeal (MP) joint. The grasp error is a weighted sum of the errors for each of these components (equation 1). The CMC flexion/extension moment was given a weighting of 1.0 and the CMC abduction/adduction moment and the index MP extension/flexion moment were given a weighting of 0.1. Synthesizing lateral grasp (key pinch) was the focus of this project, though the method can be applied equally well to other grasp patterns such as the palmar grasp. Two electrodes were used with each subject, a thumb flexor and thumb extensor. Finger flexor and/or extensor muscles were often recruited by these electrodes at higher stimulus levels, but no attempt was made to explicitly recruit those muscles.

The EMM will produce a stimulus map that will compensate for the influence of the position dependent recruitment properties as measured in the JMRCs. The influence of the time and task dependent variables on the grasp output cannot be eliminated in the open loop system. However, the appropriate choice of grasp template parameters, which are the assumed contact point and cocontraction level, can minimize their influence (See Chapter IV). The EMM also introduces some errors due to simplifying assumptions about the underlying biomechanics of the hand, and the

incorporation of moments across only one joint of the thumb and one joint of the index finger. Because muscles cross more than one joint with moment arms that vary with joint angle, and because each digit is a multi-link system, some differences occur between the grasp output predicted by the EMM and the actual grasp output. The grasp modification procedure reduces this difference through an iterative procedure.

Grasp Modification Procedure

The grasp modification procedure was based on the same assumptions as the EMM, but it used the error between the predicted grasp output and the actual grasp output as an additional input. The grasp modification procedure was initiated by measuring the grasp output resulting from electrical stimulation at each 5% command increment. The difference between the actual grasp output and the desired grasp output was used as a correction factor to calculate a new stimulus map. The correction factor was added to the grasp template moment. The altered grasp template was used as the input to the EMM to calculate a new stimulus map. The correction factor was affected by the correction factor determined for all previous iterations, but it was not affected by the values at other command levels. The influence of past iterations on the current

correction factor was determined by the following rules:

1. If the new correction was the same sign as the previous cumulative correction (initially the cumulative correction equals the correction factor for the first iteration), then the new correction was added to the cumulative correction. This corresponds to the situation where the grasp stimulus map was modified in the proper direction but not with a large enough magnitude.
2. If the new correction is the opposite sign from the previous cumulative correction and smaller in magnitude, then a new cumulative correction value is calculated as follows:

$$NC = PC - NE (NE / (2 * PC))$$

where:

PC = previous cumulative error

NE = new correction value

NC = new cumulative error

This corresponds to the situation where there was a slight overshoot in the grasp output modification.

3. If the new correction is the opposite sign from the previous cumulative correction and greater in magnitude, then the

previous cumulative correction is divided in half to obtain the new cumulative correction value. This conditions damps out oscillations that might occur when there are large errors in the grasp output due to the predicted correction moments.

The correction value is bound by a minimum and maximum value that is continuously updated as more iterations are performed. For example, if a correction of 10 N-m results in a grasp output too high and a correction of 5 N-m results in a grasp output is too low, the correction value will then be bounded between 5 and 10 N-m.

Grasp output measurement includes the position measurement as well as the moment measurement, whereas the EMM calculation is based entirely on the moment information alone. The position errors are converted to moment errors through the passive moments. The passive moment at the actual joint angle is subtracted from the passive moment at the predicted joint angle. This provides the moment error equivalent of a difference in position.

Experimental Methods

The EMGSP was implemented and tested in the laboratory with three C5 or C6 level quadriplegic individuals. All subjects were participants in a

clinical FNS program, and were users of motor prostheses which restored functional hand grasp-release. The electrodes used and muscles implanted have been described previously [22,25,37,38,40]. Briefly, two types of electrodes were used; a percutaneous intramuscular electrode and an epimysial electrode. The former is a stainless steel multistrand electrode inserted into the muscle belly. The epimysial electrode is a Pt-Ir disk that is sutured to the muscle epimysium and is used with an implanted stimulator. The electrodes are implanted in the five muscle groups. Thumb flexors include the adductor pollicis (AdP), flexor pollicis longus (FPL) and flexor pollicis brevis (FPB). Thumb extensors include the extensor pollicis longus (EPL) and extensor pollicis brevis (EPB). The abductor pollicis brevis (AbPB) is used for thumb abduction. Finger extension is achieved by the extensor digitorum communis (EDC) and finger flexion is achieved by the flexor digitorum superficialis (FDS) and the flexor digitorum profundus (FDP).

The output of each electrode/muscle combination was determined by simultaneous measurement of both thumb CMC moment (two components) and index finger MP moment. The force transducer used to measure thumb CMC forces was a six degree-of-freedom load cell (JR3., Inc., Woodland, CA). The thumb was inserted into a tube attached to the

transducer through a gimbal fixture which prevented moments from being transferred to the transducer. The arm was stabilized in the apparatus so that the wrist and forearm angle remained constant throughout the experiment. The entire apparatus is shown in Figure III.2. The gimbal pivot provided an accurate measurement of the point of force application by the thumb on the sensor. The transducer was accurate to $\pm 0.05\text{N}$ with a maximum range of 50N. The transducer was rigidly attached to a fixation device which allowed quick positioning of the thumb at any CMC joint angle. The force transducer was oriented so that the force component along the axis of the thumb went through the center of rotation of the CMC joint. Therefore, the moment about the CMC joint could be determined by measuring the moment arm between the center of rotation of the CMC joint and the force application point.

Finger MP moment was measured using a cantilever beam load cell. The finger was splinted to stabilize the PIP and DIP joints in full extension but allow free movement of the MP joint. The splinted finger was inserted in a rigid tube attached to the cantilever.

The position transducer used to determine thumb CMC joint angle was a two degree-of-freedom joystick attached to the end of the thumb. This sensor is described by Johnson, [18]. The thumb CMC angle could

Figure III.2. The force and position measurement apparatus used to measure the JMRCs for each electrode and the resulting grasp output.

be measured within ± 2 degrees over the full range of motion.

The output of each electrode/muscle combination was characterized by measuring the joint moment recruitment curves (JMRC) at various joint angles for a given level of stimulation. The JMRC for each electrode was determined through trials consisting of five discrete stimulus levels delivered in five consecutive two-second steps. The stimulus levels were 40, 80, 120, 160 and 200 μ S in ascending order for the thumb flexor and descending order for the thumb extensor. Trials at additional values of PW were performed near threshold and in high gain regions. Trials alternated between electrodes, with a 60 second rest period between stimulation of the same electrode. JMRCs were measured at five thumb CMC joint angles and two index MP joint angles. The stimulus amplitude was constant at 20mA and the stimulus period was constant at either 60mS or 80mS. The static force value for each stimulus level was obtained by sampling the force at 100Hz and averaging the force sample over the last 0.5 second of each two second step. At the beginning of each experiment, two trials were performed to warm-up each muscle [10].

The grasp output is defined as the moments and angles of the thumb and fingers as a function of the input command range (the proportional command signal). The variables measured in this project were the

moments about the CMC joint of the thumb and MP joint of the index finger, and the angle of the CMC joint of the thumb. The grasp output was measured at 5% increments of command from 0 to 100% using a method similar to that used to measure the JMRCs. Five trials, each ten seconds long, were necessary to test the entire grasp output. Each trial started with the lowest command and proceeded to the highest, simulating progressive closing of the grasp. When thumb position was measured, each trial began with a two second step at 0% command. The grasp output developed using the rule-based procedure was measured immediately after the EMGSP-generated grasp had been developed.

Thumb CMC angle was measured relative to the plane of the palm. Contact of the thumb with the index finger in lateral pinch occurs at approximately 30° CMC extension and 10° CMC abduction. Full thumb extension is typically 50° to 60° CMC extension.

Grasp Error Analysis

Two parameters were developed to allow comparisons between different grasp patterns. These parameters are the range error and slope error, and they provide quantitative values to describe the grasp output error, which is the difference between the desired grasp output (grasp

template) and the actual grasp output. The range error characterizes the grasp output at the minimum and maximum extremes of the command input. It is the percentage difference between the desired maximum force and maximum position, and the actual maximum force and maximum position, as shown in Figure III.3. For example, if the grasp output achieves 80% of the maximum desired position, then the range error will be 20%. The range error is zero if the desired ranges are met or exceeded. The range error is calculated as follows:

$$\begin{aligned} \text{PRE} &= 100 \times (1 - (A_{\text{Pmax}} / D_{\text{Pmax}})) && \text{if } A_{\text{Pmax}} < D_{\text{Pmax}} \\ \text{PRE} &= 0 && \text{if } A_{\text{Pmax}} \geq D_{\text{Pmax}} \end{aligned}$$

Where:

PRE = Position range error

A_{Pmax} = Maximum position achieved by actual grasp output

D_{Pmax} = Desired maximum position

The force range error term is calculated in the same manner.

The slope error characterizes the modulation of the force and position over the entire command range. It is the magnitude of the difference between the slope of the desired grasp output and the slope of the actual grasp output (see Figure III.3). The slopes are compared over

Figure III.3. Range and slope error values used to compare grasp outputs. The desired grasp output is shown as the line labeled "Template". The line labeled "1" shows a grasp output with a range error of 25%. The slope error is calculated by comparing the slope of the desired grasp output with the slope of the actual grasp output. The line labeled "2" shows a grasp output with a range error of 0% (maximum force is matched) but with the maximum slope error, i.e. 100% of the force is attained within one segment (5% of the command range). Grasp output "2" is defined as having 100% slope error.

each 5% command segment and the magnitude of each difference is summed over the entire command range of 100%. The slope error represents the degree to which force and position can be modulated. A slope error of 100% indicates that neither the force or position can be modulated, i.e. the grasp output can achieve only two states: maximum hand opening and maximum pinch force, with no modulation between these states. The equation for calculation of the slope error is as follows:

$$\text{Slope Error} = K \times \sum |ND_i - NA_i| / (C \times n)$$

$$ND = (D_i - D_{i-1}) / D_{\max}$$

$$NA = (A_i - A_{i-1}) / D_{\max}$$

where:

ND = Normalized desired slope (from template)

NA = Normalized actual slope (from grasp output)

n = Number of slope segments

C = Command percent per slope segment

D_i = Desired moment or position for command level i

A_i = Actual moment or position for command level i

$D_{\max}$ = Total range of force or position (typically $D_n - D_1$)

K = Normalization constant

III.D. RESULTS

The EMGSP was successfully used to develop grasps in all three subjects. The slope errors were lower for the EMGSP method than for the conventional rule-based procedure in all cases. The results are shown in Table III.2 and Figure III.5. The range errors were less than 27% and the force slope error less than 32% in all cases. For comparison, a variation in moment of $\pm 5\%$ at each measured point would result in a maximum slope error of 29% and a $\pm 10\%$ variation would result in a maximum slope error of 57%. A series of 29 trials were performed with one well-exercised electrode in the adductor pollicis. The maximum variation in moment from one trial to the next was 8% for the first five trials, and 4% for the remaining trials. Therefore, the minimum practically obtainable force slope error, given the trial to trial variations, is between 20% and 30%.

The range error was minimized within three iterations. That is, either the desired force or position range was met or exceeded, or the pulse width to the muscle reached the maximum value. Further decreases in the range error could be achieved only by adding additional electrodes to the grasp pattern.

The results indicate that the force slope error was reduced below 32% within three modification iterations. Only subject JHJ

Table III.2. EMM Implementation with Three Subjects.

Sub.	Final Max. Pos. (°)	Final Moment Range (N-Cm)	Init. ¹		Final ²		Init.		Final		Init.		Final		Num. ³ Mods.	Time ⁴ (Hrs.)
			Range Error (%)	Force Error (%)	Range Error (%)	Force Error (%)	Force Error (%)	Slope Error (%)	Force Error (%)	Slope Error (%)	Pos. Error (%)	Slope Error (%)				
MHH	51.1	103.8	35.9	44.9	21.7	22.2	44.5	57.0	22.2	84.5	57.0	57.0	57.0	3	2	1.3
JHJ	54.9	84.5	48.9	36.4	26.2	30.1	45.5	50.1	30.1	45.5	50.1	50.1	50.1	3	3	1.5
RHM	39.7	60.1	54.8	44.8	26.0	31.0	68.6	71.1	31.0	68.6	71.1	71.1	71.1	3	1	1.8

¹ The "initial" errors indicate the errors of the grasp output prior to any modifications.

² The "final" errors describe the grasp output after the last modification was performed.

³ The number of modifications are shown for both position ("p") and force ("F").

⁴ Time includes computer calculation time and the time to perform the number of modifications indicated.

demonstrated a decrease in slope error beyond the second iteration. However, the force slope error for subject JHJ decreased only 6% over all three iterations. Therefore, it is unlikely that more iterations would result in a large decrease in force slope error.

The actual force was lower than the predicted force in 21 of the possible 24 cases, indicating that fatigue was the primary cause of the slope error. If the slope error was due primarily to the position dependent recruitment properties, then the changes would be, on average, equally divided between the lower and higher actual force levels.

The grasp for each subject was developed within 1.8 hours or less. Approximately 40% of this time was devoted to computer computation and file transfer. No more than three iterations were needed to optimize the grasp for any subject. In contrast, the electrode profiling procedure currently used to synthesize the grasp stimulus map requires at least two hours to perform.

A grasp output synthesized by the EMGSP for one subject (JHJ) is shown in Figure III.4. The force slope error for the grasp output shown was 30% and the position slope error was 50%. The grasp force output matched the desired output over most of the command range. The force output over the command range from 90% to 100% demonstrated

Figure III.4. Grasp output developed using the EMGSP for subject JHJ. Three iterations were performed on the initial grasp output developed by the EMGSP.

approximately 20% fatigue from the previous iteration, which accounts for most of the variation from the desired output, as shown by the fatigue-compensated points (open triangles). The fatigue rate is high for this subject at the highest levels of stimulation because these levels are above the stimulus level used to exercise the muscle.

The position output for subject JHJ (Figure III.4) shows a deadband region from 50% to 60% command. A similar deadband region was obtained for all subjects and resulted from the small passive moment change over the lower range of CMC joint angles. The total passive moment change over the lowest half of the CMC joint angle range (about 30° to 40°) was 3 to 7 N-cm. In contrast, the change in pinch force over a comparable command range varied from 30 to 50 N-cm. Therefore the resolution in force as a function of the command range necessary to control position was as much as 10 times the resolution necessary to control pinch force.

The grasp output developed by the EMGSP was compared with the grasp output developed by the rule based method for all three subjects. The comparison of the force and position slope errors are shown in Figure III.5. The slope errors were lower for the EMGSP in all cases. The EMGSP has the additional advantage of being performed automatically, whereas the

Figure III.5. Comparison between grasp outputs developed using the EMGSP and grasp outputs developed using the rule-based method. The force and position slope errors were lower for the EMGSP-generated grasp for all three subjects.

rule based method requires extensive investigator intervention. The only disadvantage of the EMGSP is that it requires instrumentation to measure grasp force and position.

III.E. DISCUSSION

Clinical Implementation of the External Moment Grasp Synthesis Procedure

The goal of this project was to develop an automated method for synthesis of the grasp stimulus map for an upper extremity neuroprosthesis that compensates for the influence of the position dependent recruitment properties. The method developed requires measurement of the joint moment recruitment curves and utilizes an external moment model and a grasp modification scheme. This method was successfully used to synthesize the grasp stimulus map for three subjects. The grasps were developed faster and with lower errors than those developed using the rule-based method.

The results indicate that the force slope error was reduced below 32% within three modification iterations. The primary source of this error was the time-dependent recruitment properties of the electrodes, particularly

fatigue. The goal of the EMGSP is to compensate for the time-invariant recruitment properties described by the JMRC data. However, it is impossible to remove the influence of the time-dependent recruitment properties from the data. Therefore, each successive iteration incorporates data which is altered by fatigue. As a result, a 0% force slope error is an impractical goal. The trial to trial variation for a well exercised muscle, $\pm 4\%$, could result in a slope error as high as 22%, which is 70% of the experimentally obtained slope error. In addition, the slope error is further increased by fatigue from one grasp iteration to the next. A constant fatigue rate of 10% over the entire grasp output results in a slope error of 7%. If the fatigue rate varies depending on the PW, as was the case for all three subjects studied, the slope errors will be higher. In summary, the primary source of the slope error is the time-dependent recruitment properties of each electrode, and these properties can account for 70% to 100% of the experimentally obtained slope error.

The presence of fatigue in the grasp output data does not invalidate the results or the method of stimulus map synthesis. The stimulus map developed after two or three iterations will necessarily incorporate some degree of fatigue, reflecting the two to three minutes of stimulation delivered to each muscle during the synthesis process. The stimulus levels will be

slightly higher than the levels that would be obtained in the absence of fatigue, and the resulting grasp output will overshoot the desired grasp output when the grasp is in the non-fatigued state. However, after two to three minutes of use, the grasp output will approach the desired grasp output. A study of subject's usage of the neuroprosthetic system indicates that performing an activity generally involves at least one to two minutes of stimulation [17]. Therefore, the grasp output will approach the desired output for most activities. No practical advantage is obtained by attempting to remove fatigue from the grasp synthesis process.

The position output of the grasp requires the most modification, as expected. In general, position was poorly predicted using the EMGSP, with slope errors as high as 85% for the initial grasp output. It should be noted that most of the tasks for which the neuroprosthesis is currently targeted can be performed with limited modulation of thumb position. Therefore, a practical system using current standards might seek to minimize the range error and force slope error, but not the position slope error. As more accurate prediction of thumb position becomes necessary, the EMGSP will require a more complex implementation involving the measurement of moments and positions about all three thumb joints, as described later in this discussion.

The number of iterations necessary to reach a minimum solution can potentially be reduced by increasing the number of stimulus values included in the JMRC measurement. However, increasing the number of stimulus values from five to 25 adds approximately 30 minutes onto the JMRC measurement time, while decreasing the time required to perform the iterations by a maximum of 25 minutes. A good compromise is the selective measurement of additional stimulus levels in regions of high gain in the JMRC. These measurements may take five to ten minutes, while still potentially reducing the number of iterations.

The EMGSP was used in this project to develop a two electrode lateral grasp, incorporating a thumb flexor and thumb extensor. Typically a grasp pattern incorporates three or four electrodes and possibly as many as eight. For example, the lateral grasp includes a finger flexor electrode to provide full finger flexion. The number of electrodes does not affect the ability of the EMGSP to develop the stimulus map, but the computation time to reach a solution increases by approximately the square of the number of electrodes. If there is cocontraction in the grasp pattern, then the time to reach a solution is further increased. The two electrode grasps described in this paper took less than five minutes of computation time for three iterations using an IBM PC running at 7.2 MHz. A four electrode

grasp could require as much as 30 minutes of computation time on the same computer. No attempt has been made to optimize the efficiency of the software routines. However, a practical implementation allowing as many as eight electrodes will require three improvements: 1) optimization of the efficiency of the software routines, 2) utilization of a faster computer, and 3) a priori limitations on the combinations of electrodes searched.

Subjects are usually provided with both a lateral and palmar grasp [24,41]. In the palmar grasp, controlling the angles and moments of the fingers is more important than controlling the thumb moments. In order to implement the palmar grasp, it will be necessary to improve the techniques for measuring finger force, i.e. measurement of more moments and angles than just the index MP moment.

The lateral grasp template used in this paper has been developed from our clinical experience and analysis of subjects performing tasks. The template specifies a linear change in thumb CMC angle prior to contact and a linear increase in thumb CMC moment after contact [24]. However, the functional importance of the positions and forces of other joints, such as the thumb MP and interphalangeal (IP) joints, are unknown, as is the necessary resolution of each joint position and moment. Further study must be performed to determine these parameters from a functional standpoint. The

grasp synthesis method presented in this paper is flexible enough to incorporate any specification of grasp output.

Another grasp template parameter that must be determined through functional evaluations is the relative importance of the abduction/adduction CMC force component compared to the flexion/extension CMC force component. In the lateral grasp, the flexion/extension component is the most important. The relative weight of the abduction/adduction component of force was initially weighted at 10% of the flexion/extension component. The exact value of this parameter may vary depending on the tasks to be performed. However, in a two muscle system utilizing a thumb flexor and extensor, it is generally impossible to minimize both components of force independently. Theoretically, cocontraction can be used to minimize both components of force when one of the two muscles produces a large abduction/adduction component of force, but simulations which we have performed [see Chapter IV] show that cocontraction results in high grasp errors when objects of different size are acquired. In fact, attempts to minimize both force components using cocontraction actually increased the average error for both components when considered over a range of object sizes. Therefore, in a practical system, the error is minimized for one component of force and the error for the remaining component depends on

the direction of force generated by each electrode.

Extension of the External Moment Model

The method developed in this project uses relatively simple measurements of thumb CMC moment and index finger MP moment. More complex measurements could be made, including thumb MP and IP joint moments and all three joint moments of each finger. The finger MP joints can also exhibit abduction/adduction motion through the action of the intrinsic muscles. Overall, there are 16 finger moments and four thumb moments that could be measured. Only a subset of these joints can be controlled independently. Therefore, it may be necessary to measure only a subset of the available joints if the resulting moments about the other joints can be predicted using knowledge about the biomechanics of the multijoint muscles and measurement of the joint passive moments.

The EMM method does not make any attempt, by definition, to predict the actual tendon forces produced by each muscle. It is possible that a more complete biomechanical model of the hand, in conjunction with methods of predicting tendon forces resulting from electrical stimulation, may be used to more accurately predict the grasp output, particularly thumb position. This could reduce the number of modification iterations, perhaps

eliminate them entirely, thus reducing the total time for grasp stimulus map synthesis to 45 minutes or less and removing the necessity for measuring both force and position.

III.F. CONCLUSION

A computerized method for synthesizing grasp stimulus maps has been developed using an external moment model of the thumb CMC joint and the index finger MP joint. It was used to successfully develop grasp patterns for three quadriplegic individuals implemented with an upper extremity neuroprosthesis. The grasp patterns had lower errors than those developed using the previous rule-based method, indicating that the EMGSP was more successful at compensating for the electrode-position dependent recruitment properties. The EMGSP achieved the minimum force and position range errors within three iterations. The force slope error was also minimized within three iterations to less than 32%. The primary source of the force slope error was shown to be the time dependent recruitment variations, which accounted for 70% to 100% of the error. The EMGSP performed poorly at predicting thumb position. The EMGSP as used in this project could be used clinically to synthesize the lateral grasp.

IV. MINIMIZATION OF THE INFLUENCE OF TIME AND TASK DEPENDENT VARIABLES ON THE GRASP OUTPUT

IV.A. ABSTRACT

Functional neuromuscular stimulation (FNS) has been used in open loop upper extremity neuroprostheses to provide grasp and release for quadriplegic individuals. Implementation of this system requires the synthesis of a grasp stimulus map, which relates the command signal to the stimulus level to each electrode. The goal of this project was to determine methods of stimulus map synthesis which minimize the influence of time and task dependent variables on the grasp output. Minimization was evaluated using a computer simulation of the external moment grasp synthesis procedure (EMGSP) for synthesis of the grasp stimulus map [see Chapter III]. The simulation utilized a model of the recruitment curve that was generated from experimental data. The grasp output for 100 different pairs of electrodes was analyzed, each pair consisting of a thumb flexor and a thumb extensor. The influence of four time and task dependent variables on the grasp output were modelled and evaluated. These variables were: the size of object being grasped, fatigue, joint angle changes and changes

in the orientation of the hand with respect to gravity. The errors introduced in grasping objects of different sizes were reduced by selecting the appropriate joint angle at which contact is assumed to occur. The proper choice depended on the characteristics of the electrodes used to develop the grasp, and was determined by simulating each condition and comparing the resulting grasp output errors. In at least 85% of the simulated grasps, the grasp output was better if no cocontraction was included in the grasp stimulus map. It was found that the grasp output can also be improved by rejecting electrodes with high gain, thumb flexor electrodes with positive output stiffness (defined as an increase in flexion force as the thumb extends) and thumb extensor electrodes with negative output stiffness (defined as an increase in extension force as the thumb extends). These results, in conjunction with the EMGSP which compensates for the affects of the position dependent electrode recruitment properties, provide a method for determining the optimum grasp stimulus map for use in open loop upper extremity FNS.

IV.B. INTRODUCTION

Functional neuromuscular stimulation (FNS) has been used to provide grasp and release for C5/C6 level quadriplegic individuals [1,13,27,32,42,43]. Grasp and release is achieved through electrical stimulation of the forearm and hand muscles [5]. A proportional command signal supplied by the subject is used to control the grasp opening and closing [19]. The desired grasp output is obtained by developing a grasp stimulus map which relates the proportional control signal to the stimulus level applied to each electrode. Two grasp patterns are developed, the lateral grasp and palmar grasp [41]. In the lateral grasp, the fingers are flexed to form a base for thumb pinch. In the palmar grasp, the thumb is positioned in opposition and the fingers flex against it [24].

The objective in developing the grasp stimulus map is to synthesize a grasp movement and force generation that matches the desired grasp output, or grasp template [24]. The grasp output is affected by the electrode-position dependent recruitment properties and the time and task dependent variables. The position dependent recruitment properties are the threshold, gain and length dependency of each electrode [25]. These properties remain stable as long as the electrode is not dislodged. The

time and task dependent variables are fatigue¹, object size and extremity position. Extremity position influences the grasp output by 1) joint angle changes resulting in changes in the length of the stimulated muscles and 2) changes in the orientation of the hand with respect to gravity. These variables may change during use.

The goal of this project was to minimize the influence of the time and task dependent variables through the proper choice of the grasp template parameters and electrode characteristics. This was accomplished by developing a computer simulation of the external moment grasp synthesis method (EMGSP, see Chapter III), and incorporating models of the time and task dependent variables. The result of this simulation was a set of rules for determining the selection of grasp template parameters and electrode input/output criteria. Therefore, this chapter describes an enhancement to the EMGSP resulting in minimization of the influence of the time and task dependent variables on the grasp output. Chapter III described compensation for the position dependent recruitment properties using the

¹ "Fatigue" is used throughout this paper to describe the dynamically changing recruitment properties of each electrode, of which muscle fatigue is the primary component. Other components include potentiation and variations due to the fact that this is a dynamic living system with continuously varying conditions. At present, we know of no way to separate the effects of each component.

EMGSP. Taken together, these two chapters describe a method for optimizing the grasp stimulus map for an open loop neuroprosthesis.

IV.C. METHODS

A simulation procedure was used to characterize the grasp output as a function of the recruitment curve characteristics and the time and task dependent variables. The simulation was based on the EMGSP, described in Chapter III. Briefly, the EMGSP generates a stimulus map which compensates for the influence of the electrode position dependent recruitment properties. These properties are characterized by the joint moment recruitment curves (JMRC), which describe the joint moment output of each electrode as a function of the stimulus level and the joint angles. The JMRCs for all electrodes, along with the passive joint moments (including gravity), and the grasp template (desired grasp output), are the inputs to an external moment model (EMM). The EMM determines the appropriate stimulus levels for each electrode so that the predicted grasp output most closely matches the desired grasp output.

The simulation procedure used in this project was developed using models of the following components of the EMGSP: the joint moment recruitment curves (JMRC), the passive moment, the grasp output, fatigue,

object size, joint angle changes and changes in the orientation of the hand with respect to gravity. The parameters of each model were determined from experimental data. The relationship between each component of the simulation procedure is shown in Figure IV.1. The procedure is outlined here and the details of each component are described in the following paragraphs. The simulation of the grasp output proceeded in the following manner. The JMRC inputs were generated by computer using the model parameters. The grasp template, or desired grasp output, and the passive moment model, were inputs to the EMM along with the JMRCs. The grasp template contained two parameters that can be varied: 1) the point at which contact with an object was assumed to occur and 2) the cocontraction level. The EMM determined the stimulus map for the given set of inputs using a predetermined set of grasp template parameters. The grasp output was then predicted using the stimulus map, JMRCs and the passive moment. This grasp output represented the minimum error between the grasp output and the grasp template because it was not influenced by the time and task dependent variables. Simulations of the influence of fatigue and joint angle changes on the grasp output were then performed by applying these models to the original set of JMRCs. The resulting altered JMRCs are then used along with the passive moment and

Figure IV.1. The procedure used to perform the computer simulations of the external moment model (EMM). The inputs to the EMM are the grasp template, the JMRC for two electrodes (thumb flexor and extensor), and the passive moment. The output of the EMM is the grasp stimulus map which cancels the effects of the electrode-position dependent recruitment properties variables on the grasp output. The effects of the dynamic variables on the grasp output are simulated by altering the JMRC characteristics (wrist extension, fatigue), the passive force (pronation), or the contact point (object size).

original stimulus map to predict a new grasp output, which simulated the influence of fatigue and joint angle changes on the grasp output. Changes in the orientation of the hand with respect to gravity was simulated by altering the passive moment input and again predicting the grasp output. Object size variations were simulated by altering the contact point constraint in the grasp output model. This simulation procedure allows analysis of the influence of each time and task dependent variable on the grasp output. In addition, the parameters of the JMRC model can be altered so that their influence on the grasp output can be evaluated. Finally, the parameters of the grasp template can be altered to determine their influence on the grasp output in the presence of the time and task dependent variables.

One hundred simulations were performed, each representing a different "subject", i.e. a unique pair of electrodes. The simulation was tested with lateral prehension only, incorporating thumb force and position using the template shown in Figure IV.2. In the lateral grasp template, thumb position decreases linearly with increasing command input from maximum extension to contact with an object. Thumb force increases linearly from contact to the maximum force level. Each simulation utilized one thumb extensor and one thumb flexor to produce the desired lateral grasp output. The passive moment model was the same for all simulations.

Figure IV.2. The desired grasp output for contact with different sized object. This is the lateral grasp template for the thumb CMC joint.

The stimulus map for each electrode pair was developed assuming that contact with an object would occur at three different joint angles (low, medium and high) and four different levels of cocontraction (none, greater than or equal to zero, greater than or equal to 10 N-cm and greater than or equal to 30 N-cm), a total of twelve combinations. The influence of three object sizes, two arm positions affecting muscle length, two orientations of the hand with respect to gravity and at least two levels of fatigue were simulated with each grasp output. Therefore, 1200 stimulus maps were developed and at least six grasp outputs were developed for each stimulus map.

JMRC Model

The joint moment recruitment curves (JMRC) serve to characterize the position dependent recruitment properties. Each curve relates the stimulus pulse width to the joint moment magnitude and direction for a single electrode at one joint angle. The JMRC was modelled as a five segment piecewise linear function, with the slope of each segment, the direction of force and the stimulus threshold established by a statistical representation of experimental data. The methods used to measure the JMRC data used in this paper have been described previously [Chapter III,

25]. Briefly, a recruitment curve was obtained by applying a constant stimulus to the electrode and recording the resulting isometric force output. A single point on the recruitment curve was obtained by averaging the force over the last 0.5 seconds of a two to three second trial. At least five points were obtained for each curve, at $40\mu\text{S}$ intervals of stimulus pulse width from 40 to $200\mu\text{S}$. The curves were measured at one to five joint angles throughout the range of motion of the joint under investigation.

The statistical coefficients of six parameters were identified from the experimentally measured JMRC data to define the JMRC model. The parameters were 1) the stimulus threshold value, 2) the maximum force, 3) the restoring-slope scale factor (varies between segments, see description below), 4) the initial force direction, 5) the direction offset between segments and 6) the direction offset sign change factor. Each parameter was defined as a random variable with a distribution described by one of four distribution types: normal, gamma, beta, or binomial. The gamma distribution was used for those values constrained to be greater than zero. The beta distribution was used for those values constrained to be within a finite range. The normal distribution was used where there were no specific constraints on the random variable values. All the variables except the initial direction and the maximum force were considered to be

independent of the type of muscle group (thumb flexors, thumb extensors and thumb abductors). The initial direction and the maximum force had different distribution parameters for each muscle group.

A modelled JMRC has both its magnitude and direction determined from the statistical representation described above. The first three parameters are used to determine the force magnitude at each segment. The stimulus threshold (parameter 1) was the lowest stimulus level at which force was generated by the muscle. The maximum force (parameter 2) was the magnitude of the force generated at the maximum stimulus level (200 μ S). The restoring-slope for a given segment was defined as the slope that would intersect the maximum force value. It is calculated at stimulus level "X" as follows:

$$R-S = (F(200) - F(X)) / (200 - X)$$

Where:

R-S = restoring-slope at stimulus level "X"

F(X) = force at stimulus level "X"

F(200) = force at maximum stimulus level (200 μ S)

This is shown graphically in Figure IV.3..

The maximum force magnitude was a random variable exhibiting a gamma distribution. The slope of each segment was determined by first

Figure IV.3. Calculation of the restoring-slope parameter. A recruitment curve is generated by first selecting the maximum force value. The restoring-slope is the slope of the line that intersects the maximum force value with the previous segment. The restoring-slope lines for segments two and three are shown. The slope of any segment is determined by choosing a random valued scale factor that is multiplied by the restoring-slope. The shaded area represents an example of the standard deviation of segment slopes about the restoring-slope.

calculating the restoring-slope, then multiplying the restoring slope by a chosen scale factor (parameter 3), resulting in the slope value for the current segment. The slope for the final segment was set equal to the restoring slope. This method constrains the final force magnitude to the value specified by the maximum force parameter.

The direction of force at each segment was developed using parameters 4) to 6). The initial direction (parameter 4) is the direction of force at the lowest stimulus level at which force is generated. The direction offset (parameter 5) is the change in direction at subsequent stimulus levels. The force direction at each point was determined by adding the random valued direction offset to the direction at the previous point. The sign of the change can be constrained to have the same sign as the change at the previous point with a probability defined by the sign change factor (parameter 6).

The statistical coefficients of an additional set of five parameters were defined to describe the changes in the JMRC as a function of joint angle changes, specifically the thumb CMC joint. These were 1) the threshold variation, 2) the variation in maximum force, 3) the slopes and intercepts relating the average and standard deviation of the restoring-slope scale factor to the restoring-slope scale factor at the previous joint angle, 4) the

initial direction offset, and 5) the direction offset between segments. The JMRCs at each joint angle were developed by choosing a threshold, average total slope and initial direction that were based on the corresponding values at the previous joint angle. The slopes for each segment were determined from the scale factor derived for the same segment at the previous joint angle. A random scale factor for the new segment was chosen using a gamma distribution with an average and standard deviation that were determined from the following equations:

$$NSF_{Ave} = PSF \times [M_{Ave} \times (PSF) + B_{Ave}]$$

$$NSF_{Std} = PSF \times [M_{Std} \times (PSF) + B_{Std}]$$

where:

PSF = previous scale factor - restoring-slope scale factor of the
current segment at the previous joint angle

NSF_{Ave} = new scale factor - average restoring-slope scale factor of
the current segment at the current joint angle

NSF_{Std} = standard deviation of the restoring-slope scale factor of
the current segment at the current joint angle

M_{Ave} = slope for calculating average of the restoring-slope scale
factor

M_{Std} = slope for calculating standard deviation of the restoring-slope

scale factor

B_{Ave} = intercept for calculating average of the restoring-slope scale factor

B_{Std} = intercept for calculating standard deviation of the restoring-slope scale factor

The direction variation of subsequent points was determined by obtaining the average of two values: 1) the direction at the previous point on the curve being developed and 2) the direction of the corresponding point on the curve developed for the previous joint position. A random direction change was then added to this average direction to obtain the new direction.

The parameters determined from the experimental data were used to develop 100 thumb flexor and thumb extensor JMRCs. Modelled curves were used so that the model parameters could be varied and their influence on the grasp output evaluated, and to increase the number of grasp output comparisons that could be made. The statistical coefficients of the modelled curves were measured to verify that they matched the experimentally determined coefficients.

Grasp Output Model

The grasp output model was based on the assumption that the individual moments produced by each electrode, and the passive moment, can be summed to predict the total moment. This is the basic assumption of the EMM. Joint position was determined by finding the joint angle at which the sum of moments is zero. If this joint position was below the level of contact with an object, then pinch force was calculated as the sum of moments at the contact point.

The grasp output predicted by this model will essentially match the grasp template when given the stimulus parameters developed by the EMM because it uses the same assumptions. Any differences between the predicted grasp output and the grasp template are due to the discrete nature of the pulse width to each electrode (1 μ S resolution) or to situations where the grasp output cannot be matched by the given set of electrodes (e.g. insufficient force output).

Time and Task Dependent Variable Models

The grasp output in the open loop FNS system varies as a function of the conditions encountered upon grasp and release. These conditions include grasping objects of various sizes, grasping objects with the arm in

different orientations in space, and repetitive grasping resulting in fatigue. A set of four models has been developed to simulate the influence of these conditions on the grasp output. The specific conditions modelled are: fatigue, joint (wrist/forearm/elbow) angle changes, changes in the orientation of the hand with respect to gravity and changes in the size of the object acquired.

Object Size. The influence of grasping objects of different sizes was simulated by applying a minimum joint angle constraint on the grasp output model. Three object sizes were simulated: small, medium and large. The small object corresponds to the condition where contact occurs at the point of contact between the thumb and index finger. The large object corresponds to contact with an object when the thumb is fully extended. The medium object is half way between the two extremes.

Fatigue. Fatigue is manifested as a percent decrease in force magnitude. The model of fatigue consisted of an average decrease in force expressed as a percentage decrease from the initial level of force. This average decrease in force is referred to as the base fatigue amount. The exact amount of fatigue at any specific point on a recruitment curve varies from the base fatigue amount within an interval that was determined from experimental data. For example, if the base fatigue amount is 10%, the

actual decrease in force magnitude at a specific level of stimulation may range from 8% to 12%.

The fatigue model contains a second term which describes the variation in the force direction due to fatigue. It is a random variable with an average and standard deviation determined from experimental results. The fatigue model parameters were determined by measuring the JMRCs for two electrodes before and after fatigue of approximately 20%.

Joint Angle Changes. Changing the wrist, forearm and elbow angles can result in changes in the length of electrically stimulated muscles similar to the changes that occur when the CMC joint angle changes. Therefore the model representing changes in the JMRC as a function of joint (wrist, forearm or elbow) angle used the same five parameters that describe JMRC changes as a function the CMC joint angle, described previously as part of the JMRC model. The JMRC at a new joint angle was developed from the corresponding CMC angle at the initial joint angle using an algorithm identical to that used for developing JMRC from an initial CMC joint angle. JMRCs at subsequent CMC angles at the new joint angle were determined by averaging the JMRC values developed from: 1) the JMRC at the current joint angle and previous CMC joint angle, and 2) the JMRC at the current CMC joint angle and previous joint angle.

Hand Orientation Relative to Gravity. The orientation of the hand with respect to gravity is affected by the forearm, shoulder and trunk positions. Hand orientation changes were modelled as a change in the direction of the passive force vector. The magnitude of this change was determined experimentally by measuring the passive moment generated about the thumb CMC joint with gravity acting in the direction of thumb flexion and comparing it to the passive moment generated when gravity acted in the direction of thumb abduction.

Grasp Output Evaluation

The desired lateral grasp output is a linear decrease in thumb extension followed by a linear increase in thumb flexion force once contact with an object is made, as shown in Figure IV.2. The thumb is maintained at maximum extension over the first 20% of the command range while the finger position changes linearly from extension to flexion.

The grasp template contains two parameters that must be determined for each subject: 1) the point at which contact with an object is assumed to occur and 2) the cocontraction level. Simulation of the grasp output was used to determine the set of template parameters that would result in the lowest error when acquiring various sized objects. The grasp

output error values are the slope and range errors, described in Chapter III. The range error compares the difference between the actual grasp output and the grasp template at the minimum and maximum extremes of the command input. The slope error compares the slopes at each command level between the actual grasp output and the grasp template. The comparison between these two error values was made using a series of rules determined by analyzing 15 activities of daily living tasks. These tasks were developed previously to evaluate user performance with the FNS system [45, see Appendix B]. The rules are as follows:

1. The force range error is added to half of the position range error.

Approximately half of the 15 objects require opening of the hand, but all required average to maximum grasp force. Therefore the force range error is relatively twice as important as the position range error.

2. Thirteen of the fifteen objects were rigid and could be acquired with no modulation of the force slope. Therefore, the range error was used as the initial criterion for comparison. The grasp with the lowest range error was considered to be the better grasp, regardless of the slope error.

3. The force slope error was used as the secondary criterion when the grasp output developed from two or more templates had the same range error. None of the objects required position slope modulation, and

therefore it was not used to compare grasp outputs.

IV.D. RESULTS

JMRC Model. The statistical coefficients for the six parameters used to develop the simulated JMRC were determined from JMRCs measured from as many as 112 electrodes in eight subjects. These values are presented in Table IV.1. Direction of thumb force is defined as in Appendix A [and 25]: thumb adduction equals 0° and thumb extension equals 90° .

The values for the five parameters used to describe the variation in the JMRC as a function of CMC joint angle changes are shown in Table IV.2. These variations correspond to an increase in the CMC joint angle of approximately 10 degrees. A typical JMRC developed using these parameters is shown in Figure IV.4. This figure shows the moment magnitude and force direction as a function of the input stimulus level. JMRCs were developed at five successive CMC joint angles of extension, although only the JMRC parameters for the two extreme joint angles are shown in the figure.

The results indicate that if the JMRC at the initial joint angle contains

Table IV.1. JMRC model parameters

Parameter	Dist.	Ave.	Std.	Max	Min	(N) ¹	#El. ¹
Stimulus Threshold (uS)	Gamma	33	27.9	200	3	112	112
Maximum Force Magnitude (N)							
- Thumb Extensor	Gamma	5.33	2.72			12	12
- Thumb Flexor	Gamma	9.01	7.40			16	16
- Thumb Abductor	Gamma	5.51	2.69			10	10
Restoring-Slope Scale Factor(SF) ²	Gamma	1.2505	0.7966	5.0	0.0	196	38
Initial Force Direction							
- Thumb Extensor (°)	Beta	80	32	145	19	12	12
- Thumb Flexor (°)	Beta	296	19	331	264	16	16
- Thumb Abductor (°)	Beta	240	35	273	165	10	10
Dir. Offset bet. Segments(°)	Normal	-0.69	11.8	40	-40	100	38
Dir. Offset Sign Change Factor(%)Binomial [66%] ³						79	38

¹ (N) indicates the number of values used to obtain the average and standard deviation.

² (SF) indicates that the value is a dimensionless scale factor.

³ i.e. in 66% of the cases evaluated, the sign of the force direction change was the same as the sign for the previous force direction.

Table IV.2. JMRC Model Length Dependency Parameters

Parameter	Dist.	Type	Ave.	Std.	Max	Min ₂ (N) ¹	#El
Threshold Variation (us)	Normal		0.0	1.0	N.A.		
Variation in Maximum Force (SF)	Gamma		1.0198	0.2425	4.0	0.0	22
Restoring-Slope Scale Factor (SF)	Gamma	1.46-[0.312xPSF]	0.64-[0.169xPSF]				11
Initial Direction Offset (°)	Normal		1.78	12.595	50	0.0	86
Dir. Offset between segments (°)	Normal		0.78	10.229	50	-50	22
						-50	88
							11

¹ N = number of measured values.

² No quantitative data was available to describe the threshold variation due to joint angle changes, but the average change is expected to be in the range of 1 to 2us. The exact value of this parameter was shown to have little affect on the modelling results.

³ The slopes and intercepts relating the average and standard deviation of the restoring-slope scale factor to the restoring-slope scale factor at the previous joint angle. PSF = restoring-slope scale factor for the same segment at the previous joint angle.

Figure IV.4. A computer generated JMRC for a thumb extensor. Each JMRC consists of six pulse width - moment output pairs. They are developed at five CMC joint angles. The minimum and maximum joint angles are shown in this figure. Both moment magnitude and force direction are calculated for each point.

a high gain region then the JMRC at the next joint angle will tend to have the same high gain region, although the gain tends to be slightly lower. On the other hand, a low gain region is not reflected as consistently to subsequent joint angles and tends to have a higher slope on average. The slopes of each segment tend to be higher at the lower pulse widths and the maximum moment magnitude tends to be constant over the range of joint angles.

The type of distribution chosen for each parameter was determined by the constraints placed on the parameter values (see IV.C. JMRC Model). The Kolmogorov-Smirnov test was used to determine if the chosen distributions were suitable for describing the data. In all cases except the direction offset parameters, the chosen distributions could not be rejected at the 90% confidence level. The normal distribution was chosen to describe the direction offset parameter for the JMRC at the initial CMC angle and for the direction offset parameter for subsequent CMC angles, although the normal distribution was rejected at the 95% confidence level. In both cases, the data was more peaked than the normal distribution (kurtosis > 7 for both distributions, kurtosis = 3 for normal distribution). A beta distribution was also tested, using coefficients determined from the mean and variance of the data, and was also rejected at the 95%

confidence level. Therefore, the normal distribution was used for the model, and no further search was made to find a distribution with a better fit to the data. However, the direction offset was shown to have little influence on the grasp output error (see Appendix D) and therefore the results presented in this chapter are not dependent upon an exact match to the distribution. Additional direction offset data will be necessary to determine whether: 1) the data is normally distributed with a smaller standard deviation, 2) the true distribution of the data is less peaked or 3) the data is not normally distributed.

Fatigue Model. Experimental data from two muscles in one well-exercised subject was used to determine the values for the fatigue model. The fatigue amount varied from average with a standard deviation of $\pm 37\%$ ($N=7$). The direction variation had an average of -2.0° and a standard deviation of 5.7° ($N=12$).

The base fatigue amount used for modelling was 10%. This corresponds to the amount of fatigue seen in experimental sessions lasting about one hour with approximately two minutes of stimulation during that hour.

Hand Orientation Model. The orientation of the hand with respect to gravity was modelled as a shift in the direction of the passive force vector. This shift was measured experimentally for a normally innervated subject. The passive force decreased approximately one Newton in flexion when the forearm was changed from neutral to pronation. In addition, the adduction component was smaller for small angles of CMC flexion when the forearm was pronated. Therefore, hand orientation changes were modelled as a decrease in the flexion and adduction component of the passive force vector.

Influence of the Time and Task Dependent Variables on the Grasp Output

The influence of each time and task dependent variable on the grasp output is shown in Table IV.3. The template used to develop the grasp stimulus map assumed contact with a small object and allowed no cocontraction. The values shown in the table are averaged over all three object sizes (except for the line labeled "small object only"). A total of 100 grasps were stimulated with each object size. The range error when the largest object is acquired is typically small since maximum position is always achieved due to the size of the object. Therefore the range error is higher for the small object than for the average of all three objects.

Table IV.3. Task and Time Dependent Variable Affect on Grasp Output

Condition	Average Grasp Errors ¹	
	Range (%) ²	Slope (%)
Small Object only	9.88 [16.9]	16.30 [12.4]
Object Size	7.98 [14.9]	24.04 [12.3]
Arm Orientation	12.67 [15.8]	28.38 [11.1]
Joint Angle Changes	16.20 [23.1]	33.41 [10.3]
Fatigue (10%)	20.58 [21.9]	28.10 [10.1]

¹ Each error value is the average error over all three object sizes (except for the line labeled "small object only") involving 300 simulated grasp outputs. Each grasp was synthesized assuming contact with a small object.

² Standard deviation indicated in brackets.

Joint angle changes result in the largest increase in the slope error. Joint angle changes increase the range error indicating an increased variation in the maximum force for each electrode as the joint angle is changed. It should be noted that the range error is zero if the maximum force and position meet or exceed the desired force and position. Therefore, an increase in range error may indicate an increased variability in the range error and not necessarily an average decrease in the maximum force and/or position.

Changes in the orientation of the hand with respect to gravity do not greatly increase the slope error because most of the grasp output tends to follow closely the desired grasp output with the exception of a few regions where the passive force shift is manifested. The increase in the range error is due to the decreased passive flexion force, resulting in a decrease in total maximum flexion force.

Fatigue causes a decrease in both maximum force and force slope, resulting in increases in both the range and slope errors. The influence of different rates of fatigue on the grasp output was also tested and the results are shown in Figure IV.5. The fatigue rate used for comparison with other time and task dependent variables (Table IV.3) was 10%.

Figure IV.5. The affect of different rates of fatigue on the grasp output. Each error value represents the average of 300 grasp outputs consisting of 100 grasps at three object sizes. The fatigue rate used for comparison with other dynamic variables was 10%.

Electrode Selection Criteria

The electrode/muscle input/output characteristics were analyzed to determine if the grasp error could be reduced by rejecting electrodes with particular characteristics. This was accomplished by comparing the grasp output for electrodes exhibiting the highest 10% for each characteristic with the grasp output for the remaining 90%. For example, the grasp outputs developed using the ten electrodes with the highest gain regions were compared with the remaining 90 grasp outputs. Table IV.4 shows the results of this comparison. Three characteristics were identified as having the greatest influence on the grasp output errors. The joint stiffness at maximum stimulation was shown to have the greatest influence on the range error. Joint stiffness is the slope of the relationship between the CMC joint moment and the CMC joint angle at the maximum stimulus level. This relationship consists of five points, yielding four stiffness values for each electrode. A stiffness greater than zero indicates that the flexion force increases as the CMC joint angle increases, i.e. extension of the CMC joint. In 10% of the grasps one of the two following conditions occurred: 1) the thumb flexor had a stiffness that was greater than or equal to zero for all four segments or 2) the thumb extensor had a stiffness that was less than or equal to zero at for all four segments. The grasp errors for these 10%

Table IV.4. Electrode Input/Output Rejection Criteria

Characteristic	Rejection Limit	Errors: Extreme 10% / Remaining 90% ¹
Gain	> 15 N-cm/us	-37% +36%
Stiffness at max PW	> 0 TF; <20 TE	+39% +14%
Active / Passive Stiffness	< -5.0	+20% +16%

¹ The differences in grasp output between the grasps developed using electrodes above the rejection limit (10%) and the grasps developed using electrodes below the rejection limit (remaining 90%) are shown as a percentage increase or decrease. A positive number indicates that the grasp error for the extreme 10% was higher than the grasp error for the remaining 90%.

² The negative active / passive stiffness indicates an increasing extension force as a function of increasing joint angle.

were compared with the remaining 90% and were found to be higher in every category. In particular, the range error was, on average, 39% higher for the selected 10%.

The moment gain as a function of stimulus PW was also shown to have a major influence on the grasp output. The grasps developed using electrodes that had gain values in the highest 10% had slope error values that were on average 36% higher than the remaining 90% of the grasps. The range error is actually lower for the extreme 10% due to the fact that high gain electrodes tend to achieve high force levels and therefore their range error tends to be small.

A third important factor was the ratio of active stiffness to passive stiffness. Figure IV.6 shows how this factor can result in unstable regions in thumb position output. The figure shows the active extension moment for a single electrode at a constant level of stimulation over the full range of CMC joint angles. The passive flexion moment is plotted on the same axis, although it has the opposite sign as that of the extension moment. A static thumb position is achieved when the passive flexion moment is matched by an equal but opposite active extension moment. This occurs at the points labeled "1", "2" and "3" on the figure. However, point "2" is unstable. If the thumb is moved slightly into extension, the active extension

Figure IV.6. Thumb position instability due to high active to passive stiffness ratio. Points 1 and 3 are stable, point 2 is unstable. Using an electrode with this characteristic, the thumb could not be actively placed in any position between angle A and angle B.

moment increases more than the increase in the passive flexion moment, resulting in a net extension moment. This net moment will cause further increase in the CMC extension angle, which will continue until another stable point is reached, point "3". An electrode with this characteristic produces high grasp output errors because a range of thumb positions will be unattainable.

Optimum Template Parameters

The optimum template parameters were determined for 100 simulated grasp outputs. Twelve combinations of parameters were tested, involving three assumed contact points (corresponding to small, medium and large objects) and four levels of cocontraction (none, greater than or equal to zero, greater than or equal to 10 N-cm, and greater than or equal to 30 N-cm). The grasp error was determined for each grasp output when three different object sizes were acquired (small, medium, and large). The results showed that the correct choice of assumed contact point can reduce the range error by as much as 44% over all three object sizes. In 38% of the grasp outputs, the lowest error occurred when the lowest contact point was assumed. For 40% of the grasp outputs, the mid-contact point was optimum. Assuming contact with a large object was optimum in the

remaining 22%. The optimum contact point depended on the electrode input/output characteristics but could not be predicted a priori. In order to determine the optimum point, it is necessary to synthesize stimulus maps assuming contact with small, medium and large objects. The grasp output must then be predicted for all three object sizes using each stimulus map. The grasp output errors can be compared to determine which assumed contact point is optimum.

The simulation results indicated that the second grasp template parameter, cocontraction level, should generally be minimized. For 85% of the grasp outputs tested, the grasp error was minimized when no cocontraction was used. In the remaining 15% of the grasps, the optimum level of cocontraction was 30 N-cm, corresponding to cocontraction over at least 60% of the command range. Intermediate levels of cocontraction were tested, but were only optimum in less than 5% of the grasp outputs. Simulations were also performed to determine if cocontraction could reduce the influence of joint angle changes and changes in the orientation of the hand with respect to gravity on the grasp output. However, in 90% of the grasps influenced by changes in the orientation of hand, the grasp errors were lower if no cocontraction was used. The same was true of 80% of the grasps influenced by joint angle changes. Under the influence of a 10%

rate of fatigue, 93% of the grasps had lower errors with no cocontraction. Cocontraction will also tend to increase the rate of fatigue because each muscle receives a higher average level of stimulation. Therefore, cocontraction should be minimized in the open loop neuroprosthesis.

Experimental Measurement of the Task and Time Dependent Variables

The grasp output was measured under the influence of wrist extension and different object sizes for two quadriplegic subjects. The grasp output for one subject (RHM) when contact was made with three different object sizes is shown in Figure IV.7. The experimentally measured grasp output exhibits a low gain region when large and medium sized objects are acquired. For example, contact with a large object occurs at 20% command, but less than 5% of the maximum pinch force is generated at 60% command. This low gain region is due to the low forces necessary to control thumb position. The higher force levels over the command range from 60 to 100% for the large object situation are due primarily to the higher passive forces, but can also result from changes in the recruitment properties of the electrode as a function of joint angle.

The grasp output variation due to 25 degrees of wrist extension for subject MHH is shown in Figure IV.8. Thumb extension is higher over the

Figure IV.7. Experimentally measured grasp moment output as a function of command for contact with three object sizes. The desired grasp output for the large object size is shown as a dashed line. The grasp stimulus map was the same for all three grasp output measurements. The differences in the generated moment when contact is made with different object sizes is due to the length dependent properties of the electrodes and the changes in passive force at each joint angle.

Figure IV.8. Experimentally measured grasp output at two wrist angles. The thumb position shows a sharp drop from 25% to 35% command when the wrist is extended. This indicates an increase in the recruitment gain and threshold when the wrist is extended.

command region from 0 to 20% and lower from 25% to 55% command. This indicates that wrist extension resulted in increases in both threshold and force gain for the thumb extensor for this subject. The thumb flexor exhibits higher force levels over the command range of 75% to 90%, with a maximum increase of 28%. These differences in grasp output can be attributed to the change in muscle length and the passive force changes.

IV.E. DISCUSSION

The procedure for synthesis of the grasp stimulus map for upper extremity FNS has been simulated using models developed from experimental measurements performed on paralyzed subjects. The simulation was used to determine the parameters that would result in the optimum stimulus map, i.e. the stimulus map that is least susceptible to the influence of the time and task dependent variables. Reductions in the average grasp error by as much as 44% could be achieved by the proper choice of grasp template parameters.

The grasp output for two quadriplegic subjects was measured experimentally under the influence of two time and task dependent

variables: object size and wrist extension. The measured outputs are in agreement with the models of these variables. The object size model predicts that if contact is assumed to occur with a small object, but a large object is acquired, the grasp output will exhibit a very low gain region followed by an increase in force that varies as a function of the length dependent properties of the electrode. The wrist extension model predicts that the changes observed when the wrist is extended will be similar to the changes due to CMC joint angle changes. The experimental results are consistent with the modelling results, although no attempt was made to verify these models statistically.

Influence of Time and Task Dependent Variables on the Grasp Output

The time and task dependent variables increase the average range error by as much as 11% and the slope error by as much as 17%. The effects of each of these variables on the grasp output are discussed in the following paragraphs.

Fatigue is probably the most continuously changing variable which affects grasp output. Fatigue is difficult to characterize because it cannot be isolated or repeated. As a result, the exact "rate" of fatigue is unpredictable. Exercising the muscle results in properties more resistant to

fatigue, but these properties will vary from subject to subject and between muscles in the same subject [34]. Experimentally, a decrease in maximum force of approximately 5% to 20% occurs after two minutes of stimulation spread out over one hour (three seconds of stimulation followed by at least a minute of rest). Peckham, et al. [34], showed a decrease in maximum force of 0% to 50% after 10 minutes of continuous stimulation in well exercised muscles. In this project, a base fatigue amount of 10% was used for comparison with other variables. However, for tasks in which the subject uses a fairly high force level for relatively long periods of time (greater than five minutes), fatigue would become the overriding variable affecting the grasp output. These tasks would include writing and eating, where a utensil may be gripped firmly and constantly throughout the task.

In an open loop system, the joint angle at which contact will occur must be assumed in advance. When an object of a different size is acquired, the grasp output will be altered due to the length dependent properties of each electrode and the passive properties of the joint. If contact is assumed to occur with a small object, but a large object is acquired, there will be a low slope region of force increase after contact is made. If contact is assumed to occur with a large object, but a small object is acquired, there will be a high slope region of position decrease

prior to contact. These changes are due to the fact that the forces required to change thumb position are much lower than those required for thumb pinch. The changes due to the length dependent properties of each electrode will be manifested as slope variations and changes in the force range of the grasp output.

The changes due to wrist, forearm and elbow angle changes are also due to the length dependent properties of each electrode. They are manifested in the grasp output as variations in both the slope and the maximum force and position of the grasp output. These variations are magnified by the length dependent changes resulting from CMC joint angle changes when objects of different size are acquired with the wrist extended. For example, the magnitude of the influence of wrist extension depends on the moment arms of the muscles that cross the wrist. The thumb extensors have relatively small moment arms about the wrist and therefore the influence of wrist extension on the output of these electrodes would be smaller than the flexor pollicis longus and the finger flexors and extensors, which have larger moment arms about the wrist [2]. The intrinsic muscles of the hand should not be affected by changes in the angle of the wrist, forearm or elbow joints.

Changes in the orientation of the hand relative to gravity tend to alter

the grasp output at the extremes of the command range and near the contact point, but elsewhere the slope closely matches the desired slope.

Compensation for Time and Task Dependent Variables

The time and task dependent variables are those which cannot be predicted a priori in an open loop system. However, the influence of these variables on the grasp output may be minimized with the appropriate strategies as described in the following paragraphs.

The influence of different sized objects on the grasp output can be reduced by using the proper contact point in the grasp template. This point depends, however, on the characteristics of the JMRCs used to develop the grasp. Therefore, the optimum contact point must be determined for each subject individually. This can be performed by using the grasp output modelling described in this paper. The proper choice of assumed contact point can improve the grasp range error by as much as 44% in some cases.

The influence of fatigue on the grasp output cannot be altered by the grasp template parameters. The influence of fatigue may be reduced in the open loop system by developing a method of predicting fatigue at any point in time. If a reliable model of fatigue were available that allowed the

prediction of fatigue based on the time and amount of stimulation delivered to a muscle, then the stimulus parameters could be adjusted accordingly. Nathan [31,32] has proposed a model of fatigue using a wrist flexor and extensor. He only attempted to model fatigue over time for a constant level of stimulation. It is not yet known how a varying level of stimulation, such as would occur in a practical neuroprosthesis, would affect the parameters of the model. It may be, however, that the parameters of any model of fatigue change too quickly or drastically, depending on other non-measured conditions, that it would not be practically useful.

The influence of changes in the orientation of the hand relative to gravity due to changing extremity position can be minimized by developing a high stiffness system. A high stiffness system is less susceptible to changes in external forces, including gravity and passive forces. In this project, we attempted to achieve high stiffness by increasing the level of cocontraction. However, in an open loop system, increased cocontraction does not necessarily result in greater stiffness. Stiffness also depends on the length dependency of the electrodes and the passive force properties. For example, the extension force of an electrode may increase with increasing joint angle. If the passive flexion force increases with an equal but opposite amount, then the total stiffness will be zero. The addition of

a second muscle (a thumb flexor) acting as an antagonist, thus increasing the amount of cocontraction, may or may not change the total stiffness. If the second muscle has a decreasing flexion force for an increasing joint angle, then the stiffness will actually be negative, i.e. the thumb is in an unstable position. The modelling results indicate that grasps influenced by hand orientation changes tend to be lower in error if no cocontraction is used, suggesting that, on average, cocontraction does not increase stiffness.

Electrode Input / Output Criteria

The electrode input/output characteristics that had the largest influence on the grasp output were the gain, stiffness at maximum stimulation and the relative active to passive stiffnesses. The most important property of any electrode, however, is the maximum force it achieves. If an electrode cannot achieve the desired force levels, it may require conditioning to increase the force levels, or additional electrodes in the same muscle or synergistic muscles might be added to the grasp.

The output stiffness of each electrode/muscle combination was shown to have the greatest influence on the range error of the grasp output. Stiffness relates the change in force output as a function of the

change in joint angle when the stimulation is maintained at a constant level. This is also referred to as length dependency [24], and results from three causes: the length-tension property of muscle, changes in the physical position between the electrodes and nerve, and changes in the moment arm of the muscle across the joint. Of these three, the changes in the physical position between the electrode and nerve appears to have the greatest influence on the output of electrically stimulated muscles [25]. High dependence of the output on muscle length most likely occurs when the nerve fibers are drawn closer to the origin of the stimulus field as the muscle contracts. If the maximum force magnitude of an electrode increased monotonically with increasing joint angle (thumb extension), then the range error tended to be higher. This corresponds to a stiffness less than or equal to zero for a thumb extensor and greater than or equal to zero for a thumb flexor. Electrodes exhibiting these characteristics should be rejected.

High gain regions in the electrode output result from the geometrical relationship between the stimulus field and the motor nerve fibers and the fiber threshold distribution. In some cases the gain can be reduced by reducing the stimulus amplitude. This has the effect of increasing the resolution of the stimulation. Therefore it may be possible to reduce the

gain of an electrode without the need to implant a new electrode.

The most important electrode input/output characteristic that was not included in this study is spillover, or recruitment of fibers from other anatomically defined muscles. When spillover occurs to a non-synergistic muscle, it usually limits the maximum usable stimulation range of the electrode. Generally, electrodes isolated to stimulate one muscle or muscle group are the most desirable [25].

Optimum Grasp Patterns

The choice of optimum grasp template parameters depends on the functional tasks for which the grasp is intended. In this paper a set of activities of daily living was used as the "desired" tasks to be performed with the FNS grasp. However, as the grasp output and controllability become more refined, this list of tasks may be expanded, changing the relative importance between the range and slope errors. It is therefore possible that the rules for choosing an optimum grasp may change over time, but the procedures developed and presented in this paper will still remain efficacious due to their flexibility.

The relative importance between the force range error and position range error is another model parameter that depends on the functional

tasks for which the grasp is intended. For this project, the force range error was determined to be twice as important as the position range error when choosing the optimum template. However, when the force and position range errors were considered to be of equal importance, the optimum template was different for only one out of the 100 grasps tested in computer simulations. Therefore the exact relationship between the force and position range is unimportant in choosing the optimum template values.

The simulations performed in this project have resulted in three procedures for developing the optimum stimulus map. These are enhancements of the EMGSP method.

- 1) Measure and evaluate the electrode input/output characteristics.

Electrodes exhibiting high gain, thumb flexors exhibiting positive stiffness or thumb extensors exhibiting negative stiffness should be rejected. The relationship between the active electrode/muscle stiffness and the passive stiffness should be evaluated to identify potential regions of instability in the grasp output.

- 2) Develop multiple stimulus maps assuming various contact points.

Each map should be used to predict the grasp output resulting from contact with different object sizes, allowing the optimum assumed contact point to be determined.

3) Develop the stimulus map without cocontraction.

Utilization of these procedures, in conjunction with implementation of the EMGSP, results in the development of the optimum stimulus map for the open loop upper extremity neuroprosthesis.

IV.F. CONCLUSION

The use of appropriate strategies in the synthesis of the grasp stimulus map can result in significant improvement in the grasp output. The results indicate that object size, fatigue and extremity position alter both the range and slope of the grasp output. With the proper choice of the joint angle at which contact with an object is assumed to occur and the cocontraction level, the grasp errors can be reduced by as much as 44%. The optimum values depend on the recruitment properties of the electrodes used to develop the grasp pattern and must be determined on an individual basis. Further improvements in the grasp output can be accomplished by proper selection of electrodes. Electrodes exhibiting high gain, thumb flexors exhibiting positive stiffness or thumb extensors exhibiting negative stiffness should be rejected. These strategies minimize the influence of the time and task dependent variables on the grasp output.

V. CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

A computerized method has been developed for synthesizing grasp stimulus map for use in upper extremity FNS, known as the external moment grasp synthesis procedure (EMGSP). It is capable of developing the optimum stimulus map by compensating for the electrode-position dependent recruitment properties and minimizing the influence of the time and task dependent variables on the grasp output. It was used to successfully develop grasp patterns for three quadriplegic individuals implemented with an upper extremity neuroprosthesis. The grasp patterns had lower errors than those developed using the previous rule-based method, indicating that the EMGSP was more successful at compensating for the electrode-position dependent recruitment properties. The EMGSP achieved the minimum force and position range errors within three iterations. The force slope error was also minimized within three iterations to less than 32%. The primary source of the force slope error was shown to be the time dependent recruitment variations, which accounted for 70% to 100% of the error. The EMGSP performed poorly at predicting thumb position.

Minimization of the influence of the time and task dependent variables

was accomplished by developing a simulation of the grasp synthesis procedure. The influence of these variables was then evaluated as a function of various input conditions to the synthesis procedure. The results indicate that object size, fatigue and extremity position alter both the range and slope of the grasp output. With the proper choice of the joint angle at which contact with an object is assumed to occur and the cocontraction level, the grasp errors can be reduced by as much as 25%. The optimum values depend on the recruitment properties of the electrodes used to develop the grasp pattern and must be determined on an individual basis. The simulation results also indicated that cocontraction should be minimized in the open loop system. Further improvements in the grasp output can be accomplished by proper selection of electrodes. Electrodes exhibiting high gain, thumb flexors exhibiting positive stiffness or thumb extensor exhibiting negative stiffness should be rejected. These strategies minimize the influence of the time and task dependent variables on the grasp output.

The most significant contribution of this research is the development of methods for analyzing and compensating for factors that influence the grasp output. Previously, most of these factors were ignored in the synthesis of grasp patterns. Analysis of the grasp output has been typically confined to one extremity position, one object size and a single point in

time. This research demonstrates that such a view of the grasp is too limited. Each factor was shown to have a significant influence on the grasp output. The procedures developed in this project present a method for developing the optimum stimulus map for use in upper extremity FNS.

A principle advantage of the EMM method is its adaptability to various levels of complexity in the grasp synthesis process. Future implementation of this method will proceed on two levels of complexity. The first level will be aimed at quick implementation of the EMM in the clinical setting. It will involve identification of the simplest system that will take advantage of the improvements offered by the EMM over the rule-based method (automation and optimization of stimulus map synthesis). This implementation will use a minimum of instrumentation, involving measurement of the thumb CMC joint moments and index and long finger MP moments. The most important design criteria of this instrumentation will be ease of use and ease of application of the device to the subject. Both lateral and palmar grasp patterns will be developed, but no attempt will be made to modulate position of the digits beyond achieving maximum grasp opening. The grasp patterns will be developed with no cocontraction of antagonist muscles. The optimum assumed contact point will be determined by simulating three assumed contact points and predicting the

grasp errors. This system will provide automated synthesis of the stimulus map, optimization of the assumed contact point and compensation for the electrode recruitment properties in the force output of the grasp. This would be a significant improvement over the rule-based method, with the only disadvantage being the addition of instrumentation.

The second level of future implementation is aimed at improving the quality of the grasp patterns developed by the EMM. This involves the incorporation of more complex measurement techniques and a complete biomechanical model of the hand. Measurement of the moments generated about multiple joints of the thumb and fingers will be made. This information will be used to predict the forces generated by each muscle, i.e. tendon forces. The biomechanical model of the hand will be used, in conjunction with predicted or calculated tendon moment arms, to predict grasp output. The procedure for synthesis of the stimulus map will be similar except that the individual tendon moments will be used rather than the externally measured joint moments. The primary reason for utilizing these measurements is to improve the prediction of joint position using the force information. If position can be reliably predicted from the force information, it will eliminate the need to measure the position output and also eliminate the need for the modification procedure. Therefore, the

increase in the complexity of joint moment measurement will be offset by eliminating of the need for position measurement, decreasing the time required to synthesize the stimulus map from two hours to one hour.

Further improvement in the grasp output can be obtained by using sensors to provide better compensation for the influence of the time and task dependent variables. The addition of sensors could improve the grasp output significantly. The range error could be reduced 10% or more and the slope error could be reduced as much as 10%. Compensation for object size could be accomplished using a sensor that would indicate joint angle. The joint angle sensor(s) would be used to determine both angle and contact with an object, where contact would be defined as a non-changing joint angle in the presence of a changing stimulus delivered to the muscle. When contact is made, the joint angle sensor can be used to determine a new grasp stimulus map which is more appropriate for the object size indicated. A set of stimulus maps, each appropriate for a different contact angle, would be generated beforehand and stored in memory.

Compensation for the influence of wrist extension on the grasp output could be accomplished in a similar manner. Stimulus maps appropriate for different wrist angles would be developed. For subjects

utilizing wrist control, this could be accomplished without the need for additional sensors.

A gravity sensor would be necessary to compensate for changes in the orientation of gravity. The changes in passive force could be measured and the grasp parameters developed accordingly.

Complete compensation for the time and task dependent variables, including fatigue, can be accomplished using a closed loop system, such as that described by Crago, et al. [4,7]. This system involves measurement of both force and position output of the grasp. This technique has shown great promise in laboratory applications, but outpatient application awaits the availability of sensors for force and position [6], which are presently under development.

The development of the EMGSP for stimulus map synthesis provides the opportunity to utilize more detailed specification of the desired grasp output. Therefore, future research should involve analysis of functional tasks to determine optimum grasp patterns. Specifically, the following parameters should be determined: the necessary force and position resolution, the relative importance of force and position, the relative importance of each joint moment with respect to other joint moments, and the optimum relationship between the command input and the grasp output.

These parameters are currently unknown and must be determined using functional evaluations.

Four hypotheses were evaluated in this project. First, it was hypothesized that the EMGSP could compensate for the electrode-position dependent recruitment properties. Although this was difficult to evaluate because of the time varying recruitment properties, the results demonstrate that the EMGSP could compensate for the influence of the recruitment properties on the grasp force output. The second hypothesis was that the grasp output developed by the EMGSP would more closely match the desired grasp output when compared with the rule-based method. This was true for both the force slope error and the position slope error for all three grasps tested. Third, it was hypothesized that the proper choice of grasp template parameters could minimize the influence of the time and task dependent variables. It was found that the proper selection of the assumed contact point could reduce the range error of the grasp output significantly. Finally, it was found that applying selection criteria to the electrode input/output properties could reduce the grasp output.

The ultimate goal of this project is to increase the functional independence of quadriplegic individuals. The procedures for stimulus map synthesis presented in this paper are one component of a complete hand

system. As further development of each component advances, improved grasp function can be restored to these individuals.

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APPENDIX A. THUMB ANATOMY AND CONVENTION

The definition of thumb movements adopted in this paper follow those of previous papers [24,25]. Thumb extension/flexion is defined as movements parallel to the plane to the palm and abduction/adduction are movements perpendicular to the plane of the palm.

The definition of the directions of thumb force vectors or thumb movement is shown in Figure A.1.. Pure adduction is defined as zero degrees and the angles progress from adduction to extension (90 degrees), abduction (180 degrees), and flexion (270 degrees).

Figure A.1. Definitions of thumb movement used in this paper.

APPENDIX B. GRASP ERROR ANALYSIS

The slope error is normalized to the slope error for the "worst" grasp output shown in Figure B.1. This grasp is defined as having a slope error of 100%.

The relative importance between the range error and slope error, and the relative importance between force control and position control, were determined by analysis of 15 activities of daily living tasks. These tasks are collectively termed the "Common Object Test" and are used to evaluate user's functional ability. These tasks are shown in Table B.1. Each task was classified according to its size and compliance. Objects which are rigid do not require force modulation for their acquisition. Objects which are small can be acquired with no position range in the grasp output. This set of objects was used to determine the rules for selecting the optimum template, described in Chapter IV.

Figure B.1. Definition of the "worst" slope error. A grasp output with a slope error of 100% is shown by the solid line. This grasp output achieved three levels: maximum extension, rest and maximum flexion. The dotted line shows the desired grasp output.

Table B.1 The Common Object Test

<u>Task</u>	<u>Classification</u>
Drinking from a glass	large, rigid
Using a fork to stab food	small, rigid
Using a spoon to eat	small, rigid
Acquiring finger food	med, compliant
Writing with a pen or pencil	small, rigid
Typing using a pen or pencil	small, rigid
Inserting diskette in disk drive	small, rigid
Using a printer	small, rigid
Moving papers	large, rigid
Moving a book or magazine	large, rigid
Answering the phone	large, rigid
Placing a phone call	small, rigid
Brushing teeth	small, rigid
Applying toothpaste	large, compliant
Shaving	small, rigid

APPENDIX C. EMM SOFTWARE

This appendix contains more detailed descriptions of the software implementation of the external moment model, the grasp modification procedure and the grasp output model.

External Moment Model

The EMM assumes that the active moments produced by each electrode/muscle combination, and the passive moments, can be summed to predict the total moment output. This can be stated by the following vector equation:

$$(1) \quad M_1 + M_2 + \dots M_n + MP = M_m$$

where:

M_n = Moment generated by electrode n. It is a function of the joint angles (θ_1, θ_2) and stimulus level (PW).

MP = Passive moment. It is a function of the joint angles (θ_1, θ_2) .

M_m = Total moment about the joint. It is a function of the PW to each electrode 1...n and the joint angles (θ_1, θ_2) .

The model seeks to minimize the error vector (E), which is the difference between the predicted grasp output (M_m) and the desired grasp

output (M_t). This is achieved by finding the least squares solution to the set of simultaneous equations as described in the following paragraphs.

$$(2) \quad E = M_m - M_t$$

The system can be modelled as a segmentally linear system since the JMRCs and passive moments are segmentally linear relationships. The least squares solution to equation (2) is found at 21 points along the grasp input/output relationship (5% increments). The output of the EMM is a set of 21 PW values for each electrode. The PW values are assumed to vary linearly between each 5% increment. The solution for a single command - pulse width pair is achieved using the following steps:

1. Determine the desired joint angles (Θ_1, Θ_2) and joint moment (M_t) from the grasp template at the given command point.

2. Develop a mathematical description of the JMRC for each electrode at the specified joint angles. Since the JMRCs are assumed to be linear between each measured point (PW value), each linear segment can be described by a slope and offset value as shown in equation 3..

$$(3) \quad S^s \times r + B^s = M$$

S^s = slope of JMRC for linear segment s. It is a vector and

includes all three measured forces.

B^s = offset of JMRC for linear segment s . It is a vector and includes all three measured forces.

r = scalar recruitment curve value indicating a specific point within segment s . Only values from zero through one are valid.

M = vector of moment outputs for the electrode/muscle combination at point r .

3. The equation describing the sum of forces for each electrode, and the passive force, is developed by beginning with the initial linear segment for each electrode. The set of r values for each electrode are the unknowns. The general equation is as follows:

$$(4) \quad S_1^s * r_1 + B_1^s + \dots + S_n^s * r_n + B_n^s + MP = M_m$$

where:

n = number of electrodes.

S_n^s = vector of slopes of the recruitment curve at the given segment s for electrode n . It is a function of the template joint angles.

B_n^s = vector of intercepts of the recruitment curve at the given segment s for electrode n . It is a function of the template joint angles.

r_n = scalar recruitment curve value (values 0 through 1 are valid) for electrode n .

M_m = vector of total joint moments predicted by the EMM.

4. The linear least squares method can be used to find the set of r values which minimize the error vector E , which is the difference between the predicted moments and the template moments (see Eq. 2.). To implement this method, equations 1, 2 and 4 are combined and arranged in the form $Ax = y$:

$$(5) \quad S_1^s \times r_1 + \dots + S_n^s \times r_n = M_t - MP - B_1^s + \dots + B_n^s$$

5. Solve for the vector of r values using the method of singular value decomposition (SVD). With the problem stated in the form $e = y - Ax$, the SVD will find the vector x that minimizes the value of e^2 in the following manner:

$$x = (A^t A)^{-1} A^t y$$

$A^t A$ may not be invertible

Therefore, represent

$$A = L \Sigma M^t$$

L = orthonormal eigenvectors of AA^t

M = orthonormal eigenvectors of $A^t A$

Σ = square root of eigenvectors of A

Therefore:

$$x = M\Sigma^+L^ty$$

To solve:

$$z = M^tx$$

$$d = L^ty$$

$$\Sigma z = d$$

Solve for z

Solve for x, where $x = Mz$

6. If any element of the r vector is out of range (less than 0 or greater than one), the solution is invalid. A new recruitment curve segment is used for one or more electrodes and the process is repeated at step 3. Each segment is searched to find minimums that give valid r values of 0 through 1. Initially, only the segments for a single electrode is varied. If a satisfactory solution is found then the procedure is complete. If no satisfactory solution is found, then all the segment combinations are tested and the combination of segments resulting in the lowest error is chosen.

A cocontraction constraint is added to equation (5) in the following manner:

$$(6) \quad |S_1^s \times r_1 + B_1^s| + \dots + |S_n^s \times r_n + B_n^s| + |MP| = CC$$

where:

CC = cocontraction constraint value in N-cm.

The relative importance of the individual moment components (thumb flexion/extension, abduction/adduction and finger flexion/extension) can be changed by multiplying equation (5) and a weighting vector.

Grasp Modification Procedure

The grasp modification procedure reduces the errors in the grasp output which result from the simplifying assumptions of the EMM. It is based on the same assumptions as the EMM but it has as an additional input the error between the predicted grasp output (M_m) and the actual grasp output (M_a). The grasp modification proceeds iteratively until the grasp output from one iteration to the next is no longer changing or reaches a predetermined minimum value. The error vector between the measured grasp output (M_a) and the predicted grasp output can be described as follows:

$$(7) \quad [S \times r + B + MP] - M_a = E$$

where

E = vector of moment errors

M_a = grasp output vector containing each type of joint moment at a single command level.

The goal of the modification procedure is to modify the desired grasp output so that the error vector is minimized.

The modification of the stimulus map is performed by altering the initial objective function (equation (6)) of the external moment model to account for the errors measured in the grasp output. When the modification procedure is performed, each JMRC is adjusted so that the "zero" moment output corresponds to the stimulus at the command level under evaluation, i.e. the moment offset is shifted. This is equivalent to adjusting the force offset values (B_n). The values for the matrix S are not altered by the modification procedure. In addition, a corrective moment is added to the desired grasp output vector which corresponds to the magnitude of the error. For the first iteration of the modification procedure, the corrective moment is equal but opposite to the error vector. For successive iterations, the following rules apply (note that the initial stimulus map is used as the baseline regardless of the number of iterations):

1. If the new correction is the same sign as the previous cumulative correction, then the new correction is added to the cumulative

correction. This corresponds to the situation where the grasp output was modified in the proper direction but not with a large enough magnitude.

2. If the new correction is the opposite sign from the previous cumulative correction and smaller in magnitude, then a new cumulative correction value is calculated as follows:

$$NC = PC - NE (NE / (2 * PC))$$

where:

PC = previous cumulative error

NE = new correction value

NC = new cumulative error

This corresponds to the situation where there was a slight overshoot in the grasp output modification.

3. If the new correction is the opposite sign from the previous cumulative correction and greater in magnitude, then the previous cumulative correction is divided in half to obtain the new cumulative correction value. This conditions damps out oscillations that might occur when there are large errors in the grasp output due to the predicted correction moments.

The correction value is bound by a minimum and maximum value

that is continuously updated as more iterations are performed. For example, if a correction of 10 N-m results in a grasp output too high and a correction of 5 N-m results in a grasp output is too low, the correction value will then be bounded between 5 and 10 N-m.

Only one value of the solution vector r is allowed to vary during each iteration. If two muscles are active, only the muscle with the highest level of stimulation is allowed to vary. The procedure can be modified manually so that a different muscle is allowed to vary and the other muscles can be fixed at stimulus levels determined by the investigator. This situation only occurs when the desired grasp output cannot be achieved by changing the stimulus level to a single muscle because of a high gain region or a highly length dependent output.

Grasp Output Model

The grasp output model is based on the external moment model assumption that the active moments produced by each electrode/muscle combination, in conjunction with the passive moments, can be summed to predict the total moment output. This is stated mathematically in equation (1).

The stimulus level to each electrode is used as the index to the

appropriate JMRC to determine the active moment produced by each electrode. The grasp output model uses linear interpolation to determine the moment output when the thumb position is intermediate to the positions at which the JMRCs are measured. An iterative procedure is used to determine the thumb position where the sum of the moments is zero. Initially, the thumb is assumed to take the desired position specified in the grasp template and the joint moments are calculated with the given conditions. If the total moment is not zero then the thumb position is changed in the direction indicated and the joint moments are re-calculated. Both the extension/flexion angle and the abduction/adduction angle must be determined. However, given that the JMRCs are measured at discrete angles and that linear interpolation is used between them, an exact solution for the extension/flexion angle can be determined with the following equation:

$$\beta = \frac{(-\sum f m n_i) \times (\prod (m n_i - m x_i)) + \sum \{-(f m x_i - f m n_i) \times A\}}{-\sum \{(f m x_i - f m n_i) \times B\}}$$

$$A = \prod_{j=1} \begin{cases} m n_j - m x_j & \text{for } j \neq i \\ m n_j & \text{for } j = i \end{cases}$$

$$B = \prod_{j=1} \begin{cases} m n_j - m x_j & \text{for } j \neq i \\ 1 & \text{for } j = i \end{cases}$$

Note: each sum or product is over $i = 1$ to n unless otherwise noted.

where

n = number of muscles + passive moment

f_{m_i} = force at minimum angle for muscle i

f_{mx_i} = force at maximum angle for muscle i

m_{n_i} = minimum angle for muscle i

mx_i = maximum angle for muscle i

β = angle at which forces sum to zero

When β is outside the bounds of the minimum and maximum angles, the solution is invalid and another minimum and maximum must be chosen. However, there are only a few discreet joint angles at which measurements are made and therefore a valid β solution can be found quickly. An iterative procedure is then used to determine the abduction/adduction angle.

Pinch force output, rather than thumb position, is indicated when the final β angle is less than or equal to the contact angle. The moment output is then calculated as the sum of moments for the given contact angles plus the passive moment.

APPENDIX D. ELECTRODE DESIGN CRITERIA

Electrode design criteria for the three most influential input/output characteristics were determined by dividing the grasp output data into ten bins according to the criteria values, with each bin containing 10% of the simulated grasps. The maximum design limit was determined as the highest valued bin at which the average grasp output error for that bin was lower than the average error for all 100 grasps. In some cases a minimum design limit was also determined using the same criteria but using the lowest valued bin. An example of this procedure is shown in Figure D.1, which shows the low and high design limits for the electrode gain characteristic as determined from the slope and range error values. The results for all three electrode output characteristics are shown in Table D.1. These values indicate desired target ranges for each characteristic. The stiffness is expressed as the percentage of maximum force magnitude change per degree of CMC joint angle change. The maximum force magnitude should decrease between 1.5% and 2.0% for a one degree increase in CMC joint angle. The active stiffness should be less than three times the passive stiffness. The grasp output errors will tend to be lower if the electrodes used to develop the grasp have characteristics within these ranges.

Figure D.1. Design limits determined for the gain characteristic. The dashed lines show the low and high limits determined from the range and slope errors. Each bin represents a range of output gain encompassing of 10% of the electrodes. Low bin numbers represent the lowest gain values.

Table D.1 Electrode Input/Output Design Criteria

<u>Characteristic</u>	<u>Design Criteria</u>
Gain	1.0 to 3.5 N-cm/ μ S
Stiffness at Max PW	-1.5 to -2.0
Active / Passive Stiffness	% max force / degree < -3.0

APPENDIX E. MODEL SENSITIVITY

Sensitivity of Grasp Output Error to JMRC Model Parameters. A 95% confidence interval was constructed around each of the ten parameters used to describe the JMRC model. Table E.1 shows the values for these confidence intervals. A set of 100 simulated JMRCs was developed using the experimentally determined JMRC parameters except that one parameter was set to the maximum or minimum extreme of the confidence region for that parameter. The resulting grasp output errors were then compared with the errors obtained using the original parameters. The complete results are in Table E.2. The range error varied from 14.6% to 6.0% over the entire set. The range error using the original JMRC parameters was 9.9%. The slope error varied from 19.2% to 10.4% with the slope error using the original parameters being 16.3%. These variations do not alter the conclusions drawn from the simulations.

Sensitivity of Time and Task Dependent Variable Effects to JMRC Model Parameters. The sensitivity of the effects of the time and task dependent variables to changes in two of the JMRC model parameters is shown in Table E.3. Only the affect of fatigue shows any sensitivity to the model parameters. Fatigue is shown to be highly sensitive to the maximum total slope. This is because the lower average slope means that fatigue is

Confidence Intervals of the JMRC Parameters

Parameter	Min.	Orig.	Max.
Restoring-Slope SF {Ave.}	1.1405	1.2505	1.3605
Restoring-Slope SF {Std.}	0.7272	0.7966	0.8906
Initial Direction Offset {Ave.}	-3.8066	1.7784	7.3634
Initial Direction Offset {Std.}	9.6896	12.5945	17.998
Var. in Max Force {Ave.}	0.9123	1.0198	1.1273
Var. in Max Force {Std.}	0.1866	0.2425	0.3465
LD R-S SF {Ave.-Offset}	1.7636	1.4564	1.1492
LD R-S SF {Ave.-Slope}	-0.557	-0.3118	-0.0666
LD R-S SF {Std.-Offset}	1.2147	0.639	0.0632
LD R-S SF {Std.-Slope}	-0.6289	-0.1693	0.2903
Dir. Offset - Segments {Ave.}	-3.0055	-0.6855	1.6345
Dir. Offset - Segments {Std.}	10.391	11.8282	13.729
LD Dir. Offset - Segments {Ave.}	-1.3584	0.7788	2.916
LD Dir. Offset - Segments {Std.}	8.928	10.2289	11.977

Table E.1. 95% Confidence intervals about each of the JMRC parameters. The "Min" and "Max" columns represent the extremes of the confidence interval and the "Orig." represents the original value used in the modelling. Refer to Table IV.1 and Table IV.2 for further description of each JMRC parameter. "LD" refers to parameters from the length dependency model (Table IV.2).

Sensitivity of Grasp Error to JMRC Parameters

Parameter	Range Error	Slope Error
JMRC		
Default Parameters	9.88%	16.3%
Restoring-Slope SF	Max	14.61*
Restoring-Slope SF {Ave.}	Min	12.02
Restoring-Slope SF {Std.}	Max	7.89
Restoring-Slope SF {Std.}	Min	10.02
Initial Direction Offset {Ave.}	Max	10.67
Initial Direction Offset {Ave.}	Min	10.07
Initial Direction Offset {Std.}	Max	10.94
Initial Direction Offset {Std.}	Min	7.50
Var. in Max Force {Ave.}	Max	6.72*
Var. in Max Force {Ave.}	Min	14.39
Var. in Max Force {Std.}	Max	13.87
Var. in Max Force {Std.}	Min	9.26
LD R-S SF {Ave.}	Max	8.98
LD R-S SF {Ave.}	Min	9.18
LD R-S SF {Std.}	Max	13.54
LD R-S SF {Std.}	Min	11.26
Dir. Offset - Segments {Ave.}	Max	7.93
Dir. Offset - Segments {Ave.}	Min	11.73
Dir. Offset - Segments {Std.}	Max	12.2
Dir. Offset - Segments {Std.}	Min	8.52
LD Dir. Offset - Segments {Ave.}	Max	12.65
LD Dir. Offset - Segments {Ave.}	Min	9.62
LD Dir. Offset - Segments {Std.}	Max	10.89
LD Dir. Offset - Segments {Std.}	Min	10.33

Table E.2. Sensitivity of the grasp error values to the JMRC parameters. This table shows the average grasp errors for 100 simulated grasps using JMRC developed using the original parameters with the exception of the parameters listed. The "Min" and "Max" indicate which extreme of the confidence interval was used. The "*" indicates the minimum and maximum range of errors values for all tests.

Sensitivity of Time and Task Dependent Variable Affects to JMRC Parameters

JMRC Parameter	Object Size		Hand Orientation		Fatigue		Joint Angle	
	Range	Slope	Range	Slope	Range	Slope	Range	Slope
Original (Table III.3)	8.0	24.0	12.7	28.4	16.2	33.4	20.6	28.1
Max. Seg. Slp. (Ave.)	7.6	24.0	13.0	28.1	23.1	27.4	22.2	33.0
Max. Tot. Slp. (Ave.)	4.4	26.3	9.9	29.4	54.1	87.8	19.9	33.9

Table E.3. Sensitivity of the affect of the time and task dependent variables on the grasp output to the JMRC parameters.

more likely to drop the maximum force below the desired force and/or position range, thereby increasing the average range error.

Sensitivity of Grasp Output to Wrist Extension Model Parameters.

The exact magnitude of the parameters used to model wrist extension are unknown. Therefore the sensitivity of the grasp output was tested over the range of wrist model parameters shown in Table E.4. The range error varied from 14 to 20% and the slope error varied from 32.4 to 33.4%. None of the slope error variations were statistically significantly different from the range errors resulting from the original wrist model parameters and only the high average slope has a statistically significantly different range error (20.4%). Therefore, the results obtained in this project are not expected to be highly dependent on the exact parameters of the model, which probably vary depending on the muscle or muscle group under consideration.

Joint Angle Model Parameter Sensitivity

	Segment Slope		Std.	Direction Ave. (Std.)	Slope		Range Error
	Average				Error		
1.46	- 0.31P	0.64	- 0.17P	0.78 (10.23)	33.4		16.2
1.14	- 0.0P	*	*	*	33.3		14.9
1.3	- 0.16P	*	*	*	33.3		14.1
1.61	- 0.57P	*	*	*	33.1		20.4
*		0.47	- 0.0P	*	33.4		16.7
*		0.55	- 0.08P	*	33.1		16.4
*		0.73	- 0.25P	*	33.1		16.1
*		*	*	0.0 (1.0)	33.0		15.8
*		*	*	0.0 (5.0)	32.8		14.8
*		*	*	0.0 (20.0)	32.6		17.7

Table E.4. Sensitivity of the grasp output errors to changes in the joint angle change model parameters. "p" indicates the scale factor of the previous segment. "*" indicates that the default model parameters were used. The default model parameters are shown on the top line.

APPENDIX F. INITIAL INFORMATION SUPPLIED TO THE EMM

Computer simulations of the grasp modification procedure were performed to determine the number of CMC angles at which the JMRCs should be measured. The grasp output developed using information at five¹ CMC angles was compared to the grasp output developed when information at only the two extreme angles was used. In the latter case, the grasp modification procedure was used to correct the grasp output until it matched the grasp output developed using all five CMC angles. Each measurement of the JMRC at one CMC angle takes approximately five minutes. Each iteration of the grasp modification scheme takes about eight minutes. In all six cases tested it took at least four iterations to match the grasp output developed using all five JMRCs. Therefore it would take more time to modify the grasp output than to make the additional initial JMRC measurements. The results of this analysis show that it is better to start the external moment model procedure with as much information as possible and minimize the number of modification iterations necessary to achieve an accurate grasp output.

¹ Five is considered to be the maximum number of CMC angles at which the JMRCs are practically measurable.

APPENDIX G. OPTIMUM TEMPLATE PARAMETERS

The optimum template parameters (contact point and cocontraction level) were determined for 100 simulated grasp patterns. The optimum template was defined as the template which resulted in the lowest average range error. When two or more templates gave the same minimum range error, the template which resulted in the lowest slope error was chosen (see Section II). The errors were averaged over all three object sizes (total number of grasp outputs was 300) with no other time and task dependent variables affecting the grasp output. Initially, twelve templates were tested and five of the twelve templates were selected for further analysis. Table G.1 shows the parameters for the twelve templates, and the percentage of grasps in which each of the five selected templates were optimum. In 30% of the grasps tested the optimum template was one which assumed contact with a small object and allowed no cocontraction. In 33% of the grasps the optimum template assumed contact with a medium sized object and in another 22% the optimum template assumed contact with a large object. In both cases the templates allowed no cocontraction and both templates were enhanced by allowing the moment to increase linearly beyond the maximum desired moment, thus eliminating the deadband region inherent

Grasp Template Comparison

Template Contact Point	Parameters CC Level	Percentage optimum over entire object size range			
		Norm.	Orient.	Joint	Fat.
Low	None	30%	17%	18%	24%
Mid+	None	33%	39%	25%	33%
High+	None	22%	34%	37%	36%
Low	>= 30 N-cm	8%	7%	10%	6%
Mid	>= 30 N-cm	7%	3%	10%	1%

Other Templates Tested

Mid	None
High	None
Low	>= 0 N-cm
Mid	>= 0 N-cm
High	>= 0 N-cm
Low	>= 10 N-cm [†]
Mid	>= 20 N-cm [†]

Table G.1. Optimum grasp template for 100 simulated grasp patterns. The low contact point assumes contact with a small object and the high contact point assumes contact with an object at the maximum range of thumb opening. A cocontraction level of "none" indicates that no cocontraction was allowed to occur. A cocontraction level of 30 N-cm will result in cocontraction over at least 80% of the command range. The "mid+" and "high+" templates allow the force to increase beyond the maximum desired force at a constant slope. The grasp output errors are averaged over all three object sizes. The distribution of optimum templates are shown for the normal case (no time and task dependent variables), for the hand orientation case, for the joint angle change case and for the 10% fatigue case.

[†] The cocontraction level for these grasps was set to the specified value only over 15% of the command range surrounding the assumed contact point. The CC level was >= 0 elsewhere.

in the basic template for medium and large object sizes (see Figure III.2). A high level of cocontraction was only beneficial in 15% of the grasps. In general cocontraction tends to increase the grasp errors when different sized objects are acquired.

The optimum template was determined for the same 100 grasps in the presence of forearm pronation, wrist extension and fatigue. The results are shown in Table G.2. Between 20% and 33% of the optimum templates determined using only the influence of object size on the grasp output exhibited higher range errors than the optimum template determined in the presence of the other time and task dependent variables. However, in only six of the possible 300 instances was the range error more than 10% higher using the template determined using object size variations alone. Therefore it is probably unnecessary to include the affect of the time and task dependent variables (other than object size) in the determination of the optimum template parameters.

Time and Task Dependent Variable Influence on Optimum Template Choice

Template Parameters	Percentage of Grasps with Higher Range Error Using Optimum Template from Normal Situation			
	Orient. (N>10%)	Joint (N>10%)	Fat. (N>10%)	
Point				
Low	40%	1	23%	37%
Mid+	20%	0	21%	27%
High+	5%	0	0%	5%
Low	50%	0	38%	50%
Mid	57%	0	43%	71%

Table G.2. Affect of the time and task dependent variables on the optimum template parameters. This table summarizes the range errors that result when the optimum template parameters are chosen using only the object size simulations. The first column shows the percent of the grasps that were higher and the second column shows the number of grasps in which the range error was at least 10% higher. For example, the first row shows the affects of the time and task dependent variables on the grasp output when the object size simulation indicated that the optimum template parameters should assume the low contact point and have no cocontraction. When these parameters were used to develop the grasp under the presence of forearm pronation, 40% of the resulting grasps had higher range errors than the grasps developed using the optimum template parameters determined from the pronation simulation. In one case (out of 30) the range error was at least 10% higher.