Myoelectric Teleoperation of a Complex Robotic Hand

by

Kristin A. Farry and Ian D. Walker

Department of Electrical and Computer Engineering
Rice University, P.O. Box 1892, Houston, TX 77251 USA

Abstract
This paper details an unusual method of teleoperation of complex anthropomorphic robotic hands introduced in [1]: converting the myoelectric signal generated by the operator's muscles during movement into robot commands replicating the motion. This concept is not new. Myoelectric prosthetic hands have used this user interface for over two decades; however, the feasibility of using this approach for commanding more than one degree of freedom (DOF), as exemplified by the pinch type grip in current myoelectric hands, is still in question. The feasibility study described in this paper addresses myoelectric control of NASA/Johnson Space Center's 16-DOF Utah/MIT Dextrous Hand [2] for several grasping options. Myoelectric signal processing approaches, data collection apparatus, and preliminary data for key and chuck grasps are discussed.

Introduction
NASA has identified improvements in control of remote dextrous manipulation devices, or teleoperation, as critical to successful maintenance of long-lived orbiting hardware such as the Space Station [3]. Required teleoperation improvements include making the user interface more intuitive (requiring less operator training) and less fatiguing (enabling an operator to work longer shifts). As teleoperated devices increase in complexity toward that of the human hand, the 3-DOF joysticks now used to control the Canadian-built Space Shuttle Remote Manipulator System are inadequate for intuitive and non-fatiguing teleoperation. NASA is exploring alternative hand controllers for complex robotic hands such as the Utah/MIT Dextrous Hand; options include replica-type controllers and exoskeletons that fit over the operator's own hand, mapping its position directly to the robot's position.

Shortcomings of these hand controllers include large bulk and weight as well as interference with some of the motions that the operator would like to command. Perhaps more important, none offer a way of commanding force in addition to position. Consequently, NASA/Johnson Space Center (JSC) is interested in the feasibility of using myoelectric signals to teleoperate an anthropomorphic hand. The idea of low-profile skin-surface electrodes placed on an operator's forearm which do not interfere with hand motion and which could be used to detect force exerted by and possibly position of an operator's hand is quite appealing.

At the same time, users of hand prostheses would like additional DOFs in their prostheses, which now offer only a single-DOF pinch-type grasping. However, many multiple-DOF prosthetic hand designs such as the Swedish Hand [4] have focused on control issues[5]. These problems parallel those faced by the space teleoperation community: the user interface must be intuitive and non-fatiguing to enable practical long-term use of the device. In fact, the problem faced by the amputee is larger than that faced by a teleoperator: a teleoperator can focus entirely on controlling a remote device for lengthy periods, but an amputee cannot be productive if a large portion of his or her energy and concentration is spent controlling an artificial hand.

An extensive review of the myoelectric control literature indicates that either the space teleoperation or prosthesis improvement scenario requires advances in the state of the art of myoelectric control. NASA and a group of medical and prosthetics specialists, prosthetics users, and insurance industry representatives collaborated in a 1991 workshop to identify research objectives in prosthetic hands [6]. The medium-term objectives of this coalition include improvements in myoelectric control to improve hand positioning and grasping. These objectives guide our research at Rice University.

We have begun with exploring the feasibility of myoelectric teleoperation by a fully-limbed subject, as we believe that this defines an "upper bound" on the performance of myoelectric control with limb-deficient prosthetic users. We are emphasizing myoelectric signal processing techniques that will result in "intuitive" control of multi-fingered hands on the order of complexity of the Utah/MIT Dextrous Hand. This paper outlines our approach in determining the extent of myoelectric control possible with normally-limbed subjects. It covers a brief
Related Previous Work in Robotic Hands and Grasping

The theory of grasping and manipulation by multifingered hands has been the subject of much research in the past decade. (See, for example, the books by Mason and Salisbury [7] and Cutkosky [8]). A number of sophisticated algorithms for grasp synthesis, mechanics, and control have been proposed. Some robot hands have been constructed and tested, notably the Utah/MIT Dexterous Hand [2] and the Salisbury Hand developed at Stanford [9]. The anthropomorphic nature of the Utah/MIT hand made it a logical choice for our myoelectric teleoperation study.

These robotic hands are complex testbeds for evaluating grasping strategies. Currently, however, the experimental state of the art lags the theory and many algorithms suggested are too complex or require sophisticated sensors now unavailable. One promising approach has been suggested and validated by Speeher [10]. He uses a small set of basic grasp primitives, each of which is simple to program. This approach seems well-suited for application to teleoperation using a probably small set of myoelectric signals.

In this work, we seek to identify a set of basic motion primitives and distinguish between them in the myoelectric signal. We will then adapt Speeher's work to teleoperate the robot hand.

Related Previous Work in Prosthetic Hands

Working prior to the robotic hand research efforts, the prosthetics community reached a rough consensus that there are five types of grasp important in a person's daily activities: (1) three-jaw chuck or pincher grasp used to hold small objects; (2) lateral grasp, most often called a key grasp because it is used to hold a key while unlocking a door; (3) hook grasp, used to carry items such as books or a briefcase; (4) spherical grasp, where the thumb and fingers are wrapped around a spherical object; and (5) cylindrical grasp, where thumb and fingers are wrapped around a cylindrical object [11, 12, and 13]. Some consider the spherical and cylindrical grasps to be variations of the ability to make a fist. Others argue that the flattened hand (with thumb rotated completely out of opposition of the fingers) is also a grasp of sorts, as it is essential in supporting flat objects such as trays.

The relative importance of these grasps is a function of an individual user's occupational and personal needs. Commercially available prostheses are capable of the chuck grasp, with the capability to open the fingers in a two-jaw pincher fashion to give some cylindrical grasping capability. More advanced prostheses such as [14, 15, 16, and 17] have incorporated chuck and key grips, with spherical and cylindrical grasp options being provided by passive finger compliance. Weight, size, cost, and reliability of the added functionality of these advanced prostheses were major reasons why they never became commercial products; however, recent advances in miniaturizing hardware and lowering power consumption and costs suggest that these problems may now be secondary to the control/user interface problem. In fact, the longest (over 15 years) multi-function hand project, the Swedish hand, ended with this conclusion [4]. Hence, our work focuses on improving the myoelectric user interface. In this paper in particular, we explore new ways to myoelectrically command grasping primitives.

Related Previous Work in Myoelectric Control

Space does not permit a thorough description of the physiology of muscles; the reader is encouraged to read [18], [19], and [20] for physiological and mathematical descriptions of the development of the myoelectric signal during muscle contraction. Briefly, an electrode placed on the skin surface can measure the passing of the action potentials propagating along muscle fibers underneath the electrode as the fibers contract. Skeletal muscle fibers are innervated (and hence stimulated to contract) in small groups known as single motor units (SMUs), the smallest voluntary contractable group. A single action potential in an SMU is associated with a twitch; sustained contractions require repeated firings (resulting in a string of action potentials) of an SMU. As more force is needed, more SMUs are fired or recruited. The electrode records the sum of all of these action potentials after they have propagated through the tissue to the skin surface.

Research in using the resulting myoelectric signal (also called the electromyographic or EMG signal) to control environments or prostheses dates from the late 1940's [21]. By the early 1970's, researchers were treating the myoelectric signal as an amplitude modulated signal whose amplitude was roughly proportional to the force developed in the muscle generating it. The consensus was that most of the information in a myoelectric signal was in the amplitude [18]. By the late 1970's, the model had matured to treat the myoelectric signal as amplitude modulated Gaussian noise whose variance is proportional to the force developed by the muscle [22], [20]. Consequently, commercial myoprocessors used in prosthesis control are now based on only one dimension of the myoelectric signal, the force level, and in a few
cases, its rate of change. Researchers have successfully refined force estimation from the myoelectric signal [23], [24], [25], [22], [20], [26], and [27]. Parker's work forms the basis of control of multiple functions using different force levels on a single channel [20]. Hogan's work was particularly significant in eliminating low frequency noise from the force estimates due to the spatio-temporal sampling artifact inevitable with skin surface electrodes [18], [26]. Jacobsen [27] refined use of the rate of change of force in elbow control of the Utah arm. A version of the Swedish Hand used rate of change of force to switch control functions [16]. We investigated these force estimation results in operating a proportionally controlled grasp force with a three-fingered robotic hand.

These force estimation techniques require a separable muscle contraction for each function commanded, making simultaneous control of two or more joints very difficult. A number of researchers, beginning with Wirta and Taylor [28], examined linear combinations of myoelectric force estimates from multiple channels to select different functions. The Swedish Hand developers applied these methods to selecting wrist and grasp [29], [4], [30]. The Japanese research team applied the technique to wrist control in the Waseda Hand 3 [14]. Jacobsen [31] and Jerard [32] extended and formalized the mathematics for this approach and applied it to upper limb above-elbow prostheses. These force-estimating approaches require at least one electrode pair and signal processing channel for each muscle used, up to a dozen in some above-elbow experiments. Furthermore, force estimating myoprocessors can be used only on superficial muscles [26], while most motions involve both superficial and deep muscles. In fact, any deep muscle activity reaching a force estimating myoprocessor is erroneously interpreted as superficial muscle activity.

Thus, previous simultaneous control multi-function systems based on the force-estimating philosophy have required tedious tailoring to each individual and do not allow for day-to-day variations in individuals. Even after extensive training, clinical tests of this approach have shown that amputees must concentrate on the contractions to consistently reproduce desired myoelectric patterns [4]. The effort involved has resulted in amputee rejection. It appears that all information in the myoelectric signal must be exploited, rather than just the force estimate, in order to obtain multifunction sensitivity that is intuitively easy to use. Furthermore, we must use information from deep as well as superficial muscles.

Some researchers have considered shape and spectral characteristics of the myoelectric signal in addition to force estimation. Recent findings suggest that there is considerable information in the myoelectric spectra, if we can understand its coding. Examples include:

1. Small muscles generally have fewer fibers per SMU and therefore have power spectra containing more high-frequency activity than larger muscles with larger SMUs [33].

2. Tissue (including other muscles) between the active muscle and the measuring electrode acts as a low pass filter to myoelectric signals, thus excessive low-frequency power densities may indicate cross-talk from adjacent muscles [33].

3. Action potential conduction velocity decreases with fatigue, causing gradual shifts in power to lower frequencies during sustained forceful contractions [33].

4. SMU recruitment order is stable for a given task [34]. Short-time spectra of myoelectric signals associated with a given rapid movement does not vary as much as previously thought [35].

The full spectrum of the myoelectric signal has been examined using techniques involving statistical patterns and spectral analyses [36], [37], [38], [39], [40], and [41]. Evidence of movements having distinct spectral signatures has been reported by Lindstrom and Magnusson [33], DeLuca [34], and Hannaford and Lehman [35]. The spectral signature of the initial muscular recruiting phase of arm motions to select up to six functions of an upper limb prosthesis from a single myoelectric signal has also been exploited recently by Hudgins [42].

**Approach**

Hudgins' [42] use of spectra-related parameters such as zero-crossing and slope changes and Hannaford's [35] use of Short Time Fourier Transforms (STFT) analysis led us to focus on the time-varying spectrum of the myoelectric signal in our myoelectric teleoperation research. We are studying the correlation between the myoelectric spectrum in the initial recruiting phase of a motion with the type of motion. We are following the lead of Saridis [39], Doerschuk [40], Kelley [41], and Hudgins [42] in using multiple-muscle myoelectric signals instead of the traditional single-muscle signals. However, our work differs from previous work of other researchers in that we are using the actual frequency spectrum to discriminate different grasping motions. Also, previous work has focused on arm, not hand, motions and on parameters derived from the spectrum rather than the actual spectrum.

**Experimental Setup**

Assisted by NASA/JSC, we developed a myoelectric data collection system to capture up to eight myoelectric data streams while simultaneously recording the motion of the subject's hand and arm.

Figure 1 is a diagram of the data capture system. We use EXOS™ exoskeletons (EXOS, Inc., Cambridge, MA)
to measure the subject's joint angles. The hand EXOS (Figure 2), originally used by NASA/JSC as a master to teleoperate the Utah/MIT hand measures joint-angle related parameters for four joints on the thumb and each of three fingers (index, middle, and ring) [43].

Figure 3 shows a channel of the Grass Instruments (Quincy, MA) Model 12 amplifier used to measure myoelectric signals. It consists of a differential amplifier, a high-pass filter (with roll-off frequency adjustable from 0.01 to 300 Hz) to block DC and motion artifact, a low-pass filter (adjustable from 30 to 20,000 Hz) to limit aliasing, an adjustable-gain amplifier stage, and isolation to protect the subject from electric shock hazards of power supply and computer equipment. This sequence amplifies the differential myoelectric signal from skin-surface electrodes (around 1 millivolt in amplitude) to several volts. Differential input reduces the 60 Hertz interference (typically much larger than the myoelectric signal) from lights and equipment.

Both exoskeleton and myoelectric amplifiers are connected through Burr-Brown MPV950S A/D boards to 68020-based Ironics IV3204 and IV3201 microcomputers. These capture up to 32 channels of data at 1000 samples per second per channel. Data are transferred to MATLAB format disk files by an 80386 Radix PC after each data run. The A/D and Ironics and Radix computers are on a VME bus and do double duty as the control computers for the Utah/MIT hand, with which we plan to demonstrate myoelectric teleoperation. We use Math Works’ (Natick, MA) MATLAB software, Version 4, for off-line data analysis and plotting.

**Preliminary Results**

Our first use of this system has investigated direct use of the myoelectric spectrum to differentiate the key and chuck grasps. Other grasps -- hook, cylindrical, and spherical -- will be considered later.

The key and chuck grasps differ only in thumb position relative to the fingers. The thumb opposes the side of the index finger in the key grasp, while it opposes the tips of the index and ring fingers in the chuck grasp. A study of anatomy suggests that differentiating between these grasps requires measuring muscle activity in the palm (especially the thenar prominence) of the hand (where important thumb opposition muscles lie) as well as the forearm (where finger and some thumb extensors and flexors lie). If we are to keep the operator's hand free of movement-encumbering hardware (in the teleoperation scenario) or develop techniques which have any chance of application to the amputee community, however, we must restrict ourselves to use of the forearm muscles. Thus our early experiments measured two myoelectric signals from a point on the forearm (Figure 4). The first measurement is the difference between the posterior and anterior electrodes, while the second is the difference between the medial and lateral electrodes. These electrode positions ensure that the myoelectric signal includes contributions by many muscles in the forearm (including the deep thumb extensors, abductor, and flexor). We used adhesive electrodes and a 20 Hz high-pass filter to reduce electrode motion artifact. The low-pass filter roll-off was 500 Hz, to limit aliasing.
Wearing the hand exoskeleton and electrodes, the subject did a series of key grasps and a series of chuck grasps with the lateral side of the forearm resting on a horizontal surface. We made no attempt to control the starting position (a relaxed posture) or grasp precisely -- the subject was the judge of consistency in these positions. We then zeroed 59-61 Hertz frequency components (to remove power supply noise) and all frequencies below 5 Hertz (to remove most of the motion artifact and dc bias) from each myoelectric data stream (typically 2 or 3 seconds long). Next, we used the exoskeleton data to locate in each data stream the beginning of the hand motion, the point at which any finger joint exceeded 5% of its eventual excursion from the starting position. Then, we took a 200 ms window of myoelectric data whose 50 ms point corresponds to the beginning of the hand motion. This window position and size was based on findings by Hudgins et al [42] at University of New Brunswick (UNB), who reported finding a deterministic component of the biceps and triceps myoelectric signal during the early (initial muscle recruiting) portion of arm motion. This 200 ms window of data, which we call the UNB Analysis Window, was frequency transformed by

\[
X(k) = \sum_{j=1}^{N} x(j) e^{(j-1)k - iN}, \quad \omega_N = e^{-2\pi i/N}
\]

using MATLAB’s Fast Fourier Transform (FFT).

The resulting spectra magnitudes were averaged across channel and grasp for each data-collecting session (typically ten grasps of each type). Figure 5 shows results from one channel in one session with normalized averages for ten key and ten chuck grasps superimposed. There are differences in the frequency distributions for the two grasps in the 100-200 Hz region which may be exploitable in classifying the grasp signatures.

To trace this frequency distribution difference to a physiological cause, we measured single muscle myoelectric spectra for superficial forearm muscles with varying attributes: elbow flexor Brachioradialis (BR); wrist extensors Extensor Carpi Radialis Brevis (ECRB) and Extensor Carpi Ulnaris (ECU); finger extensor Extensor Digimidtum Complex (EDC); and thumb extensor/abductor pair Extensor Pollicis Brevis (EPB) and Abductor Pollicis Longus (APL). To isolate the individual muscle, we placed 10mm electrodes approximately 10mm apart on the skin over the muscle belly. Use of superficial muscles only helped equalize tissue filtering effects. The subject performed motions such as extending the thumb (EPB/APL) or abducting and extending the wrist against resistance (ECRB and ECRL) to contract the monitored muscle.

We computed the spectra of the resulting 3-second myoelectric signatures (including the initiation and steady state phases of the motion) with MATLAB as above. We then computed the frequency coordinate of the center of area under each spectrum. Figure 6 shows the relation between one subject's spectrum centroids and typical muscle fiber length and mass fraction from Brand's cadaver study [45]. We are still refining this experiment, but believe that these preliminary data show correlation between the myoelectric spectra and physical characteristics of muscles as suggested by DeLuca [34]. Of particular interest is the EPB/APL pair's frequency centroid (around 160 Hz); this pair is active in the early phase of the chuck grip but not the key grip. Its activity could account for the added energy between 100 and 200 Hz in the chuck grasp's initiation spectrum (Figure 5).

In the past few years, there has been significant
progress in Time-Frequency Analysis [44]. These techniques identify both time- and spectra-related characteristics of signals. They have been applied successfully to other non-stationary signals and we are evaluating their merit in this application. We are now using Short Time Fourier Transforms (STFTs) to study the time variation of the myoelectric frequency spectra during the course of a hand movement. Hannaford and Lehman [35] noticed patterns in the STFT of the myoelectric signal from neck muscles engaged in rapid head movements; our initial findings suggest these techniques will prove useful for analysing myoelectric signals from hand motion.

Conclusions and Future Work
This is the second year of an on-going project on the feasibility of myoelectric teleoperation. Our goals include myoelectrically controlling the Utah/MIT hand in a demonstration of removal of two types of push-in-and-
pull" (PIP) pins commonly used to secure spacecraft hardware. These two types of pins ("L" and "T" handle) require grasps similar to the key and chuck grasps, but this is only a beginning. For example, differences in the myoelectric signature for constrained as well as unconstrained motion must be understood in order to control force applied to the release buttons on the pins.

The above results for key and chuck grasps are preliminary; we are collecting more data for these and other grasps using different electrode positions. We have begun work on methods for anticipating the myoelectric signature to guide our electrode position choices. Analysis must be done to ensure that we are seeing more than just measurement and motion artifact. Grasps done while using unrelated muscles in the arm to support the arm or wrist may also be studied, to determine if these effects are separable. We will cover these issues in our conference presentation and future papers.

We also plan to broaden our analysis to more subjects. The frequency signatures will vary from individual to individual as well as change somewhat from day to day for a given individual. A method to differentiate hand motion from myoelectric signals must be applicable to any individual on any day and be insensitive to imprecise electrode positioning. This robustness must be achieved without excessive repetitive user training. We will explore scenarios for the implementation of a frequency-based scheme in an operational real-time system. Filter banks are one such scenario. Spectral estimators are another. Finally, as we develop implementable scenarios for myoelectric teleoperation, we will begin a parallel effort to determine their applicability to control of multiple degree of freedom hand prostheses capable of multiple grasps.

Our initial results suggest that myoelectric commanding of grasp primitives for the Utah/MIT hand is feasible. If our goal of making the control both intuitive and repeatable is achieved, a myriad of opportunities in both robotics and prostheses development could open up.

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