

CONTROLLING POWERED UPPER EXTREMITY PROSTHESES NOW AND IN THE FUTURE

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HISTORY

Powered prostheses have come a long way in the last twenty five years. A good way to track this activity is simply to review the proceedings of the Myo-Electric Controls (MEC) conferences that have been held during that time. Some of the highlights are listed here especially those that led to further developments. Two-electrode threshold control, three-state control, quick-slow control, cookie crusher voluntary open control, proportional control, shifting of control to a second device, control using a force servo, the positional servo control, simultaneous control of two or more devices, circuits with plugs or switches to select an optimal control scheme for a particular user, the interfacing of a computer to let the prosthetist tune the control system to the user, the use of a computer to store complex control programs that can be downloaded to the control system to test their suitability for the user, voice activated control, the use of RF to isolate the setup computer from the prosthesis, and much more.

TECHNOLOGIES THAT ARE CHANGING THE RULES

During the last decade a number of new technologies have become available to prosthetics researchers. Listed below are some that seem particularly important. A few are almost available, but are close enough to reality that they will drive our future plans. For the most part the prosthetics field has to wait until a mass market develops a technology that can be adapted.

Batteries with Improved Power Density

Since 1975 the capacity of a nickel based rechargeable AA cell has gone from 550 mAHr to over 1100 mAHr and environmentally friendly Ni-MH cells have for the most part replaced Ni-Cd. Where high current is not an issue, Li-Ion and Li-polymer cells are replacing the nickel types with two cells replacing five. The lithium cells solve the memory problem, but they create a new problem, since their voltage falls substantially during use. Ten years ago that seemed like a problem, but now it is easy to put a microprocessor into the device using the batteries. This processor not only enables proportional control of speed and force, it also supplies current to the motor with pulse width modulation (PWM) so that the system responds as if the battery voltage were constant.

Better Motors, But Not Better Gear Reduction

As magnetic materials have improved, motors have become much more powerful for the weight. However, electric motors are only efficient when they run at high speed. A great deal of weight is still used to transform high-speed, low-torque rotation into low-speed, high-torque motion, and energy is wasted in the transformation. Further, to truly mimic the human body one needs to move joints quickly at low speed and then instantaneously shift to high torque.

Distributed Control Systems

It is no longer necessary to put all of the control circuitry in one place. Soon we will send commands from a central processor to local controllers at each device. The need for an industry-wide protocol for this type of control is discussed below.

Configurable Control Systems

Almost every component manufacturer now provides a way to configure its system using a computer interface. At first this only meant that gains and thresholds could be set for myoelectric signals. Now users can quickly switch between setups as different as all myoelectric control of three devices by two muscles and positional servo control of one device with myoelectric control of two devices.

Implantable Myosignal Transducers

Simultaneous acquisition of signals from surface muscles and the muscles buried underneath has always been a problem. While several groups have contrived ways to extract some of the information present in the underlying muscle using multiple features of the myoelectric signal, [4, 5] nothing works as well as direct acquisition of the myosignal. You will read about one implantable myosignal transducer in these proceedings. A second group is also working to advance this technology. One or both will probably be approved for use in amputees before the next MEC conference. These units are about the size of a large grain of rice, and they acquire their power from outside the body using RF energy. Either RF or infrared light is used to deliver their outputs which may be partially or fully processed myosignals.

Improved Materials and Techniques for Making Sockets

To support the new control systems better light-weight prostheses are needed. The wide availability of high-modulus materials combined with the training of prosthetists in their use has been essential to the development of better powered prostheses. The need is for automating the production of outstanding patient interfaces so that more prosthetists can achieve the results that now come only from a small cadre of specialists.

INTUITIVE PROSTHETIC CONTROL

The most intuitive prosthesis control uses the original muscles to control the same functions in the prosthesis. This is already done when biceps and triceps are used to control the motion of a powered elbow joint. What are the problems with this approach, and how will they be solved?

Full Control Needs Two Muscles per Degree of Freedom

Relatively few muscles are lost during a transradial amputation, but after higher level amputations, only a few large muscles remain. Elsewhere in these proceedings Kuiken et al will report on the current state of research on subdividing muscles and on connecting severed nerves to them. The goal is to create enough myoelectric signal sources to replace all of the muscles that have been lost. The challenge is to perfect techniques for subdividing muscles and nerve fascicles. Identifying which fascicle does what may be particularly challenging. To date this research has relied on surface myoelectric pickups.

Coping with Muscles Too Deep for Surface Myoelectrodes

In many cases good muscle signals are already available for controlling prostheses intuitively. These are often the signals present in muscles too deep for surface pickups. The implantable transducers discussed above will make these muscles usable. Implantable signal pickups will also improve the signals from nerve-implanted muscles because the re-ennervated muscle bands can then be made smaller without excessive crosstalk between adjacent bands.

Creating a Mechanism That Responds Like a Human Arm

At present, electric elbows need to be locked when not moving to conserve power. Some engage lock pins and others use reverse locking clutches. Neither approach permits the mechanism to exhibit the compliance of a natural joint. In contrast the muscles of the intact arm act like variable stiffness springs. To gain compliance while still using electric motors, one can place nonlinear springs between the motors and the two joint directions. [1] With a lock, only one motor is needed to move the joint in both directions. With nonlinear springs, two motors are needed. Some weight can be saved by using a powerful direction motor with a slower weaker motor being used to change the stiffness. Adding motors increases weight. To avoid this some workers are looking at pneumatic control with electronics relegated to controlling the gas flow. Such a scheme needs a source of compressed gas. Michael Goldfarb has developed such a system, and it will be interesting to see if it can be made to fit in an arm prosthesis. [2]

The Human Brain Commands a Position Not a Speed

A few years ago Matt Smits at the Liberty Mutual Research Center studied the triphasic myoelectric signal generated when a traumatic amputee suddenly tried to reposition his prosthetic arm. [3] What was curious was that a long-term amputee could still generate such a signal. In the intact arm, it is normal, because the central nervous system (CNS) first generates a large impulsive muscle contraction to accelerate the forearm, then an impulse to stop it in the new position and finally a small third impulse to damp out the second. Experiments of this sort are best comprehended by using a set point model for muscle control. The CNS operates by commanding new set points for the levels of muscle activity. The CNS is certainly not sending speed control signals like our present control systems.

The Two-Step Control System

The goal for future control systems will be to create an accurate model of the human joint system. Myoelectric signals will reset the parameters in the model on a continuing basis, and the model in turn will control joint motion using improved mechanisms. The mechanisms will have settable levels of compliance and stiffness, and will respond much as a normal human arm. The ideal mechanism will only need power to reset the mechanism state. For instance a short burst of motor power will increase or decrease the tension in a spring. Inherent in such a system is the use of spring elements to compensate for gravitational loads.

Proprioceptive Feedback – the Missing Element

Amputees have to rely on eyesight for most of their location feedback. In addition motion of the elbow or shoulder shifts sufficient mass that socket pressures alter supplying additional feedback. However, small changes in wrist orientation or finger position cannot be detected this way. Feedback is so important that many amputees control their elbow position with a positional servo rather than with the more intuitive myoelectric signals from the biceps and triceps. The servo is a popular scheme for controlling the elbow because the user gets position information from the position and spring tension in the servo transducer without watching the prosthesis.

THE HUMERAL ROTATION PROBLEM

High level amputees lose the ability to position the terminal device accurately in space because they have lost internal and external rotation. There are three cases that must be considered. Case one covers almost all transhumeral amputees at present. These persons lose

their epicondyles, and even though they can still rotate the humerus, this rotation cannot transmit force to the prosthesis and thus accomplishes nothing. Case two covers the small number of persons who have received a Marquardt angulation osteotomy or who have implanted metal pseudo-epicondyles. [6, 7] For these persons a socket can be built that transfers humeral rotation into rotation of the prosthesis. This motion is under complete natural control. A third case is those persons who have received the benefits of osseointegration. Here the end of the humerus is rigidly attached to the prosthesis keeping the control completely natural with the added advantage that with osseointegration the user senses forces on the bone and which supplies some proprioceptive feedback.

Help for case-1 amputees

With a socket that stabilizes against inadvertent rotation, a simple rotation lock is the first component to add. This scheme is offered in the RSL Steeper Mark 14 Elbow and by a rotation lock made by Rim Jet [8] to go between the conventional elbow and the upper arm socket.

Richard Weir is reporting on a powered humeral rotator at this conference. There are no "left over" myoelectric sites to control this motion. However, the control muscles are almost always intact and only await the appearance of implantable myoelectric pickups to function.

The author has suggested another approach – to implant a powerful bar magnet in the end of the humerus and to use giant magneto-resistive sensors to detect humeral motion. This approach requires a drive like the one Weir will discuss.

RESEARCH SPONSORED BY THE U.S. DEFENSE DEPARTMENT

Early in 2005 the U.S. Department of Defense initiated two projects to improve the performance of upper extremity prostheses. The sponsoring agency is DARPA (Defense Advanced Research Projects Agency.) One initiative has a two-year time line and the other is for four years. The emphasis is on the transhumeral amputee with some attention being paid to shoulder disarticulation.

Goals of the DARPA Prosthesis 2007 Two-Year Project

The project [9] is designed to "improve the capabilities of upper-extremity prosthetic limbs beyond those currently available commercially by increasing range of motion, strength, endurance, and dexterity." The short term goal is to deliver a single prosthetic arm system suitable for transhumeral and shoulder disarticulation amputations leveraging recent advances in neural sensing & control, control systems, actuation, power storage and distribution, freeform manufacturing, micro fabrication, sensory feedback, flexure and transmission design, and signal processing. Some of the quantitative goals are arm free swing, local control, state sensing & task-based mode shifting within the device, simultaneous control of 3-5 joints, fingertip force sensing, local hand grasp slip control, elbow lift capability up to 20 ft-lb (27 Nm), grip strength up to 25 lbf (111 N), wrist flexion strength up to 1.67 ft-lb (2.26 Nm), robust intuitive control, 24 hour endurance until refuel or recharge, a minimum of 3 grasp patterns: fine pinch, lateral pinch, and power grip, wrist 2 degrees of freedom, humeral rotation, effective cosmetic cover, noise level below 50dB(A) at 1 meter, water & grit resistant, automated system for fitting to residual limb, modular to accommodate various stump lengths

Goals of the DARPA Four-Year Project

The following goals are excerpted from the DARPA website: [10] chronically implantable neural interfaces, sensory (afferent) feedback to the nervous system, able to differentiate afferent and efferent signals, simultaneous control of joints, internal hardware viable in vivo more than 1 year, biomimetic kinematics meaning a hand capable of a complete grasp set and an arm with free swing like an intact limb during walking, inertial properties that match the lost limb, weight, shape and appearance similar to an intact limb, robust in typical indoor and outdoor environments, amenable to direct skeletal attachment, wearable for 18 hours per day, modular to accommodate various stump lengths, effective cosmetic matching.

One can get an idea as to how functional this prosthesis is to be by looking at the following list of tasks that an amputee is expected to be able to accomplish: writing sample sentences, turning over 3" x 5" cards, picking up small common objects (e.g., paper clips, bottle caps), simulated feeding, stacking checkers, picking up large light objects, and picking up large heavy objects.

THE CHANGING ARCHITECTURE OF PROSTHETIC CONTROL SYSTEMS

Life was simple when all that was available was a hand with a bidirectional bridge and threshold electrode amplifiers for triggering open and close motion at fixed speed. Or was it? Even a simple system needed many unique polarized plugs with wires of many lengths.

The seven degree-of-freedom arm being discussed at this conference has 21 wires in 3 shielded cables crossing the elbow, and all but 4 are used. There are only four conductors passing through the most popular wrist rotator, and yet some people want to feed back grip force information while others want absolute position for true servo control of grip. Using a separate wire for every function already gives a lot of problems. Surely more complex systems will have to be put together differently.

The Need for a Common Industry-Wide Information Bus Structure

With Otto Bock, Motion Control, Liberating Technologies, and two DARPA contractors all meeting the same challenge of controlling more devices simultaneously, now is the time to create a standard bus structure for the industry. By the end of MEC'05 we should have a working group to begin the required discussions. Within four months there should be a white paper defining the problem. Some of the issues to be addressed are contained in the following list.

1. What will the power bus look like? Will there be a standard voltage, for instance the output of two Li-Ion cells between full charge and discharge. Can we find a connector that will fill the needs of most companies?
2. Will we need a chip-to-chip bus like the SPI bus in the Boston Digital Arm and in many similar systems?
3. Will we use a high-speed serial bus? If so what will the highest frequency be, and will special shielding be needed to prevent interference?
4. How many lines are needed in the information bus? Will there be an agreed voltage for supplying the information bus electronics?
5. What cables and connection schemes will be used to daisy chain the bus?
6. The scheme used by Bock to connect the rest of the system to the electrode amplifiers solves the problem of stocking cables of many lengths. Can this idea be carried into the standard bus structure?

7. Can we agree on a standard protocol for doing computer interfaces? Do we use cables and optoisolation, or is it better to standardize on a wireless technology?
8. Implantable myosignal detectors will be in use soon. Can we agree now how the information will be coded for transmission by RF or by visible or infrared light?
9. What conditions will be dictated by US and EU regulations?

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