International Journal of Surgery (2007) **5**, 436–440

INTERNATIONAL JOURNAL OF SURGERY

www.theijs.com

REVIEW

Sensory motor systems of artificial and natural hands

Paul H. Chappell*, **Andy Cranny**, **Darryl P.J. Cotton**, **Neil M. White**, **Steve P. Beeby**

School of Electronics and Computer Science, University of Southampton, Highfield, Southampton SO17 1BJ, UK

KEYWORDS
Upper limb;
Prosthetics;
Hand;
Neuromuscular

Abstract The surgeon Ambroise Paré designed an anthropomorphic hand for wounded soldiers in the 16th century. Since that time, there have been advances in technology through the use of computer-aided design, modern materials, electronic controllers and sensors to realise artificial hands which have good functionality and reliability. Data from touch, object slip, finger position and temperature sensors, mounted in the fingers and on the palm, can be used in feedback loops to automatically hold objects. A study of the natural neuromuscular systems reveals a complexity which can only in part be realised today with technology. Highlights of the parallels and differences between natural and artificial hands are discussed with reference to the Southampton Hand. The anatomical structure of parts of the natural systems can be made artificially such as the antagonist muscles using tendons. Theses solutions look promising as they are based on the natural form but in practice lack the desired physical specification. However, concepts of the lower spinal loops can be mimicked in principle. Some future devices will require greater skills from the surgeon to create the interface between the natural system and an artificial device. Such developments may offer a more natural control with ease of use for the limb deficient person.

Introduction

Historically, Ambroise Paré (1509–1590) is recognised as the father of artificial hands.[1–3] He was a French military surgeon and made an artificial hand that was anthropomorphic with spur gears and levers to move the fingers individually. It was designed for wounded soldiers. Sadly the peaks of activity in research and development for prosthetic hands still coincide with the events of major conflicts around the world.

One of the major challenges and frustrations in upper limb prosthetics is providing a person with an artificial hand that has a natural appearance, anthropomorphic movement and can be operated easily. Trans-radial amputation results in not only the loss of the hand structure, but also the signal pathways which provide sensory information and motor function. However, the control of a hand is retained in the brachial plexus. The natural system has a mechanism with many independent movements (degrees of freedom), resulting from 27 bones and associated muscles, joints and

---

* Corresponding author. Tel.: +44 2380 593442; fax: +44 2380 593709.
E-mail address: phc@ecs.soton.ac.uk (Paul H. Chappell).

1743-9191/$ - see front matter © 2006 Surgical Associates Ltd. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijsu.2006.06.028

tendons. In contrast, present day myoelectric hands are restricted to just a single degree of freedom (DOF). Their design has changed little since the introduction of the first devices in 1960s[4] with a single motor driving the first and second fingers in unison with the thumb to produce a tripod grip. The main changes have been an increase in grip force and speed of closure of the hands due to improvements in the electrical motors and smaller more powerful batteries. Two such examples are the Otto Bock SensorHand™ Speed[5] and the Motion Control Hand.[6] These hands are capable of holding an object such as a ball very well and grasping the handle of a suitcase. In order to accommodate a wider range of objects requires more degrees of freedom and hence more actuators (motors). Adding more degrees of freedom means adding extra weight which is unacceptable due to the discomfort for the users in the form of pressure points in the socket that attaches an artificial hand to their stump. The problem of designing a multifunctional hand has been addressed by several different research groups in the form of prototype prosthetic devices.[7,8] These devices are made possible by adopting a lower grip force strategy and hence use smaller and lighter motors within the prosthesis. Conventional single DOF myoelectric prosthetics can produce a grip force of about 100N. It is believed, however, that by increasing the functionality of a device to allow for more prehensile grip patterns that can more readily support irregularly shaped objects then such high forces are not required. The current limit for a prototype hand is six motors (Fig. 1).[8] Each finger can flex and extend while the thumb also has medial rotation. Power from each motor causes movement through a planetary gearbox and worm/wheel. This arrangement is used so that when there is no power, the fingers and thumb are locked and an object will be held, removing the need for a break-locking mechanism which is required in a tendon actuated hand.

A similar multiple DOF hand, also using a worm wheel gear configuration, has been developed by Touch Bionics. This iLimb Hand™ is about to undergo clinical trials and should be commercially available in the near future.[9]

To introduce more functionality, the components required for a myoelectrically controlled hand are EMG signals, sensors, controller and mechanism (Fig. 2). This figure illustrates the concept of feeding back signals from sensors to measure the position of the fingers and thumb, to notify when the skin surface makes contact with an object (touch) and to indicate possible slip of an object from the hand's grasp. From a physical science point of view this concept means the measurement of relative position, force and object velocity. A high specification is required for these sensors.[10]

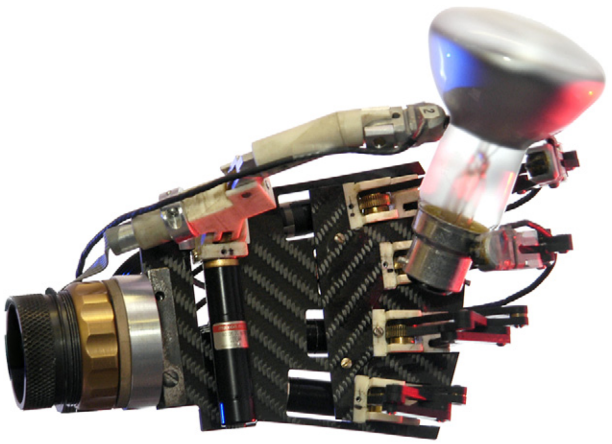

Figure 1 Southampton Remedi Hand with six independent movements.

Currently one or two EMG signals are used to allow a person to open and close an artificial hand. A muscle is voluntarily contracted to form a signal that is proportional to the degree of opening of a hand. Ideally a person will give a minimum of cognition into grasping and manipulation of an object. In concept the anatomical structures can be directly connected to an artificial system. For example, an ideal situation would be where a person merely thinks about gripping a key to open a lock where the thumb opposes the lateral side of the first finger and the task is carried out. This vision is one of the science fiction for film makers to digitally conjure up. Maybe one day it will be possible for a skilled surgeon to identify a single nerve fibre which is connected to a motor unit in the extensor carpi radialis muscle and attach a small electrode to it. The signals travelling along the nerve can be amplified and sent to a controller which activates a motor to carry out a particular movement. However, one of the problems is that the natural components are distributed. For example a muscle does not have only one signal from a single nerve as an electric motor does. Instead there are multiple signals with parallel paths operating on different motor units within the muscle. A further complication is that the motor units are activated on a random basis over time. An electronic controller for an artificial hand will be required to process the impulses from parallel paths into a useful and meaningful signal that can then be combined into one signal to control a DC motor. As the smaller motor units are recruited first followed by the larger units this information will also have to be combined with the single channel.

Artificial hands can look very natural through the use of a silicone cover called a cosmesis.[5] Skin tone, texture, blemishes and superficial veins can be included for individual requirements. A further design aim is to make a hard-wearing cover that during movement of the fingers and thumb does not store too much energy through elastic deformation. If a cosmesis is designed incorrectly, then there is less force available for gripping which places additional power requirements on the system.

Southampton Hand

The aim of the Southampton Hand research is to both fabricate a device that has multiple degrees of freedom and to develop algorithms that allow for the automatic holding and manipulation of objects. The overall features of such a hand are given in Table 1.

Physiological system

A simplified representation of the physiological system is shown in Fig. 3 where cognitive commands form the motor cortex descend the spinal cord. Signals travel to the α-motor neurone, along the α-fibre to the motor unit causing

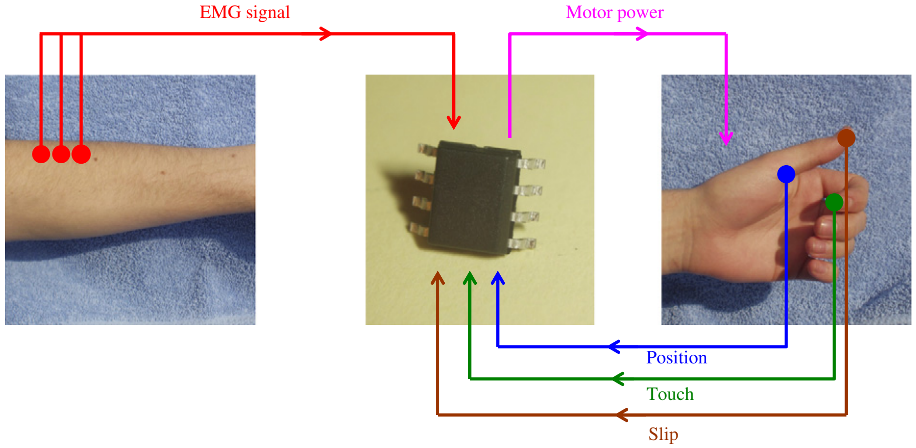

Figure 2 Illustration of the input from EMG signals to an electronic controller for automatic object grasping using position, slip and touch signals.

force to be applied to a load. In series with the muscle are Golgi tendon organs which act as tension (force) sensors to allow for a negative feedback control loop. In parallel with the muscle is the spindle which measures length (distance) and velocity (rate of change of length). Changes in length of the Golgi tendon organ can also vary muscle activity using the γ-nerve signals (stretch reflex). There are other parts to the system, which are not shown in Fig. 3, such as the antagonistic muscle, inhibitory signals and loops that allow the natural flexor/extensor system to operate. The system is much more complex than this with many parallel paths.[11,12] An artificial hand can be made which mimics the simplified concepts of the natural system. By measuring current in a DC motor, the torque generated (and hence force at a finger tip) can be determined. Also position (length) and velocity signals can be used in a feedback control system (called a servomotor). In contrast such a system does not have any parallel paths and also a single motor can act as both the flexor and extensor ''muscle''.

Table 1 Specification for an artificial hand

A day's use from one battery pack
Anthropomorphic in shape
Combined grip force of 40N
Easy to operate by the user
Electronic controller
Independent movement of fingers and thumb
Input signals from no more than two EMG signals
Interchangeable finger mechanisms — modularity
Lightweight — less than 500 g
Maintenance period of six months
Multifunctional
Multiple sensor sites especially on the finger tips
Natural covering — cosmesis
Natural movement
Noiseless in operation
Operating temperature range −10 to 40 °C
Retains grip on object when there is no power
Sensors for touch, slip, position and temperature

The natural sensory system for touch further complicates the simplified system shown in Fig. 3. There is also sensory information from joint position (finger position), slip detection, touch, temperature and pain.

A person will use information from their senses to create learned patterns of movement which will improve their performance in carrying out a task. As an example, consider the training that a racing car driver experiences. The first time a person drives round a race track, they will be using their senses with higher neural levels to navigate and become familiar with the layout of the track. As they have more practice, the time to complete a circuit will decrease. A point will be reached when the car is moving so fast that they are using learned patterns to move their trunk, limbs, hands and feet in the negotiation of bends rather than for example an eye—brain—muscle movement-sensory feedback loop. There is simply not enough time for the signals to travel round the cognitive loops and still maintain control of the car.

Artificial slip sensor

An alternating signal is produced from a slip sensor that picks up the small variations between the two moving surfaces of the skin and object. This movement can be detected as small acoustic or vibration signals which are then converted into voltage signals. Using thick-film technology, signals centred around 1 kHz are generated. Fig. 4 shows the signal when an object is accelerated from rest under free fall of gravity with a light grip on the object. Notice at the beginning, the amplitude is small which increases towards the middle of the waveform with an increase in frequency content of the signal. This signal represents the relative velocity between the two surfaces and upon processing (rectification with a threshold) can be converted into a signal representing the distance slipped as shown in Fig. 5. This signal grows in steps over time and it increases by a count of one, every time the rectified signal exceeds a threshold value. So the processing involves the counting of events which produces an approximation to the integration of slip velocity. A benefit of using slip sensors in a feedback loop is that an automatic increase in grip force can be achieved.

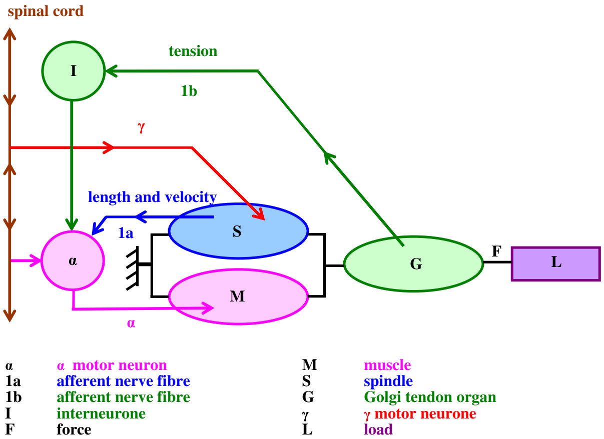

Figure 3 Diagrammatic and simplified representation of a muscle fibre showing force and length sensors.

Artificial temperature sensor

Picking up a very hot frying pan activates a temperature sensor in a person's hand, resulting in the automatic release of the pan (withdrawal reflex). Physiologically, a withdrawal reflex is crucial in preventing tissue damage but is unlikely to damage a cosmesis. This type of reflex can be incorporated into an artificial hand through the use of thick-film temperature sensors. An alternative approach would be to retain a grip on the hot object and through an audible signal, warn the user. If the temperature exceeds a certain value, then it could be released and any damage to the hand be avoided. A more intense audible signal could be made to tell the user that the object is going to be dropped. Similarly a warning signal could be made if a cold object is grasped. A temperature sensor can be used to compensate for any variations in the performance of other sensors and electronics (temperature drift), achieving fault free operation in artic or desert conditions where the temperature variation can be extreme.

Future developments

With improvements in materials and actuators more degrees of freedom will be included with a target weight of less than 500 g. There will also be a corresponding decrease in power consumption. New sensors will be developed that will have intelligent systems within them. Connections from the motor neurones to DC motors via an amplifier would result in direct control of hand movements. However, this arrangement would require implanted electrodes and may be difficult for the person to coordinate any movements due to the difference between the natural parallel pathways and the single motor actuators. Also stimulation of peripheral nerves, muscle motor point and motor cortex has shown plastic changes in the motor cortex organisation where the afferent input has a significant impact on the induced changes.[13,14] This evidence suggests that a person may be able to adjust their natural pattern generators of neural activity to compensate for the replacement of a natural hand structure with an artificial one. Another possibility is the processing of EEG signals which requires the person to have an array of electrodes on their head or implanted electrodes. Further, there has been brachial plexus nerve reinnervation onto a deinnervated and segmented pectoralis muscle in order to provide suitable multiple muscle sites for coordinated hand control.[15] Development of electronic sensors also provides the opportunity for the surgeon to connect wires into the sensory system providing direct feedback to the amputee of the state of an artificial hand.[16] Imagine that a person is driving a racing car and has an artificial hand. The information about the patterns of movement could either reside in the neural system or in an electronic system. With future developments, some way will need to be found of electronically interpreting the nerve impulses that the surgeon has provided. There will be need for signal processing in the interface between the electronic sensors and the natural sensory nerves. Also signal processing for the interface between the α-motor nerves and the artificial actuators will be required. However, whatever surgical procedures and future technology are developed they will provide different choices for the physically disabled to improve their everyday quality of life.

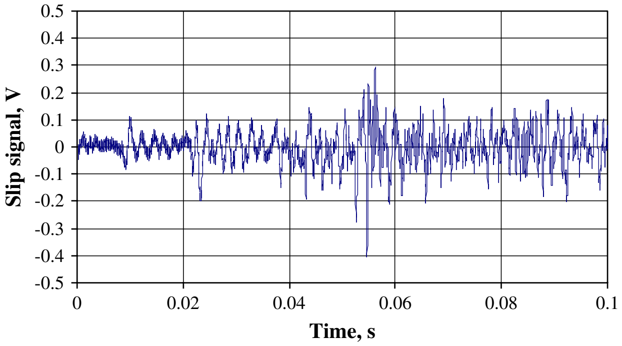

Figure 4 Signal from a slip sensor.

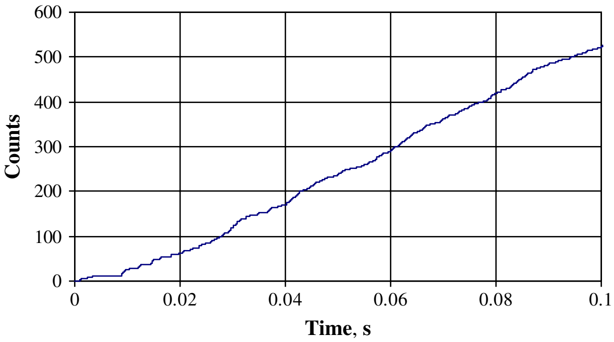

Figure 5 Processed slip signal representing distance an object has slipped.

Ethical statement

The research reported on in this paper has not required experiments on human subjects. No ethical approval has therefore been requested.

Acknowledgements

The authors wish to thank the Engineering and Physical Sciences Research Council (EPSRC) of Great Britain for their financial support under grant number GR/R95470. Thanks are due to Mark Long for making the components of hands and sensors.

References

1. Delaruelle L, Sendrail M. *Textes choises de Ambroise Paré*, vol. 31. Paris: Les textes Français; 1953.
2. Lyons AS, Petrucelli II RJ. *Medicine an illustrated history*. New York: H N Abrams; 1987.
3. *The new encyclopaedia Britannica*. In: *Micropaedia ready reference*. 9th ed., vol. 9. Chicago: Encyclopaedia Britannica; 2002. p. 736.
4. Childress DS. Historical aspects of powered limb prosthesis. *Clin Prosthet Orthot* 1985;**9**:2—13.
5. Otto Bock, <www.ottobock.co.uk>; 1985 [accessed 03.04.06].
6. Motion control, <www.utaharm.com/tds.htm>; 1985 [accessed 06.04.06].
7. Sebastiani F, Roccella S, Vecchi F, Carrozza MC, Dario P. Experimental analysis and performance comparison of three different prosthetic hands designed according to a biomechatronic approach. In: *Proceedings IEEE/ASME international conference on advanced intelligent mechatronics*. AIM 20—24 July 2003, vol. 1. p. 64—9.
8. Light CM, Chappell PH. Development of a light weight and adaptable multiple axis hand prosthesis. *Med Eng Phys* 2000; **22**:679—84.
9. Touch bionics, <www.touchbionics.com>; 2000 [accessed 03.04.06].
10. Cranny A, Cotton DPJ, Chappell PH, Beeby SP, White NM. Thick-film force, slip and temperature sensors for a prosthetic hand. *Meas Sci Technol* 2005;**16**:931—41.
11. Wolpert DM, Zoubin G. Computational principles of movement neuroscience. *Nature Neuroscience* 2000;**3**:1212—7.
12. Wolpert DM, Miall RC, Kawato M. Internal models in the cerebellum. *Trends Cognit Sci* 1998;**2**(9):338—47.
13. Ridding MC, Uy L. Changes in motor cortical excitability induced by paired associative stimulation. *Clin Neurophysiol* 2003;**114**:1437—44.
14. Charlton CS, Ridding MC, Thompson PD, Miles TS. Prolonged peripheral nerve stimulation induces persistent changes in excitability of human motor cortex. *J Neurol Sci* 2003;**208**:79—85.
15. Miller LA, Lipschutz RD, Weir RW, Williams TW, Stubblefield KA, Heckathorne CW, et al. Shoulder disarticulation fitting with 6 independently controlled motors after targeted hyper-reinnervation nerve transfer surgery. In: *Myoelectric controls/powered prosthetics symposium*. University of New Brunswick, Fredericton, Canada; Aug 2005. p. 21—4.
16. Dhillon GS, Horch KW. Direct neural sensory feedback and control of a prosthetic arm. *IEEE Trans Neural Syst Rehabil Eng* 2005;**13**:466—72.