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Experimental development of a sensory control system for an upper limb myoelectric prosthesis with cosmetic covering

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Abstract—A sensory control system based on the force-sensing resistor (FSR) for an upper limb prosthesis has been designed for application to a commercial prosthetic hand of proven reliability. In particular, FSR sensors have been used to control the strength of the grip on objects. Moreover, the problem of the object possibly slipping from the grip has been addressed by a system based on an optical sensor for detecting movement. Tests on different everyday objects have shown the feasibility of the above approach, given the constraints of the limited dimensions of the prosthesis and the presence of a cosmetic glove.

Key words: *automatic grip, FSR sensor, involuntary feedback, optical motion sensor, slip detection.*

INTRODUCTION

The hand is the fundamental organ for the demonstrations of creativity typical of man. Its loss, either from birth or owing to an accident, is therefore a highly dramatic event, for both the practical and the psychological consequences it entails; in such circumstances, it is thus advisable to provide a suitable prosthetic device.

In the last few years, advanced robotic hands, with various fingers capable of different movements, have been developed, which have potential for use in the prosthetic field. For example, the Stanford/JPL hand consists of 3 fingers, each with 3 degrees of freedom (DOF), controlled by 12 actuators; the Utah/MIT hand—one of the greatest achievements in the development of an anthropomorphic robotic hand—has 4 fingers, each with 4 DOF, and 32 actuators; the Belgrade/USC hand consists of 5 fingers and 4 motors (1,2). From a prosthetic point of view, there is the difficult problem of the control of these sophisticated devices by the user, although studies on the subject can already be found in the literature (3–5). However, the versatility and the functionality of an artificial hand is not determined only by the degree of mechanical complexity, that is, the number of DOF available; another very important issue is the presence of a sensorial system that can enable the grip to be optimized and tasks to be carried out efficiently and rapidly. The central role of the sensorial system in a prosthetic hand has been understood since the 60s: in those years the Army Medical Biomechanical Research Laboratory developed the AMBRL hand, which had a slip sensor on the thumb to increase prehension when a slip occurred (6). More recently, pressure sensors along the surface of the fingers and encoders that determine the degree of rotation of the fingers with respect to the palm have been mounted on the Belgrade/USC hand. Significant studies in the field of sensorial systems for prostheses have also been carried out by Chappel and Kyberd at the University of Southampton. They have realized the sensorial system of the MARCUS hand, which is also an example of an advanced prosthesis, as a result of an EEC project in which the Centro Protesi INAIL took part (7,8).

The MARCUS hand consists of three fingers: a thumb, an index, and a middle finger; the last two are

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connected at the base of the phalanxes. Both the fingers and the palm of the hand have sensors; this enables, in suitable phases of the hand's functioning cycle, the recognition of contact with an object and any possible slipping of the same. Therefore, the motors operate in such a way as to ensure an optimal contact and an increase in the strength of grip sufficient to avoid slipping.

At Centro INAIL, the prosthesis that is generally fitted on clients is the Otto Bock myoelectrically controlled cosmetic hand. This prosthetic hand does not have the same versatility as those mentioned above, since it is characterized by a pincer-like movement (that is, it has only one DOF); it is, however, well known for its high reliability, and that has contributed to making it a standard (9). Another issue that we also consider to be of great importance is the satisfactory cosmetic covering: the Otto Bock hand consists of the mechanical part, an underglove covering it, and the actual cosmetic glove, available in 18 shades so that it can be well adapted to the natural skin color of each individual.

The problem of the appearance could seem to be of secondary importance with respect to the functionality of the prosthesis. In fact, in Northern Europe and the United States prostheses of the pincer or even hook type are frequently used. On the other hand, appearance is an important issue in Mediterranean countries, where it is often the cause of considerable problems of psychological nature and of social reintegration. In fact, the loss of a limb leads to a physiological process known as "working through of a bereavement" that may, if not sufficiently completed, cause narcissistic phenomena to arise, to the level of real forms of psychosis. It is clear that such an event also has consequences on social relations: the person with amputation often experiencing difficulty in relationships with partners and family members and a reluctance to be reintegrated in employment. To provide at least a partial remedy to these problems, it is therefore necessary to fit a prosthesis that is valid from two points of view: functionality and appearance (10,11).

In order to increase the functionality of the Otto Bock hand, our aim was to fit it with a sensorial system, bearing in mind that this should not compromise the appearance. Respect for this aim leads to many difficulties: for example, the sensorial system of the MARCUS hand, although advanced, is not capable of functioning if there is a cosmetic glove: the controller continues to receive information from the sensors, but since this is incorrect, it can result in totally inappropriate actions.

METHODS

"All or Nothing" and Proportional Control Prostheses

To have a good understanding of the importance of the application of a sensorial system, it is necessary to describe the functioning of a prosthesis without it.

The prostheses produced at the Centro INAIL up to a few months ago were of the "all or nothing" type: the EMG signal caused by the contraction of two remaining muscles in the residual limb (typically the flexor and the extensor muscles), detected by means of electrodes, produces the opening or closing of the prosthetic hand at the fastest speed possible (depending on the voltage of the power supply), for the whole contraction time. Metering of the movements is thus obtained by means of a sequence of microcontractions. The use of the prosthesis is consequently rather difficult, or at least awkward, especially in the manipulation of objects with little mechanical resistance. Recently, the fitting of proportional control prostheses has begun: the speed of movement and the strength applied to an object in the grip phase are proportional to the intensity of the muscular signal; it is thus possible to better meter these elements, in order to obtain a finer control of the prosthesis.

Sensorially Controlled Prostheses: Involuntary Feedback Control System

The control system of the above-described prostheses lacks any form of feedback, or more exactly the only form is the visual feedback of the wearer. Visual control does, however, require considerable attention by the user, who must continually keep his/her eyes on the actions of the prosthesis, and that can be tiring. It is clear that the aim is to obtain a subconscious control, similar to the control of natural limbs. In other words, one would like to realize a control system that really depends on feedback of an involuntary kind, with no explicit act of will required (**Figure 1**).

This objective can be achieved by providing the prosthesis with sensors: strength sensors and possibly slipping sensors.

The information from the strength and slipping sensors can be sent jointly to the control system, that is in this way informed when the hand is grasping an object with enough strength to keep it from slipping. If it is slipping, the control system can automatically order the actuator of the prosthesis to increase the grip strength.

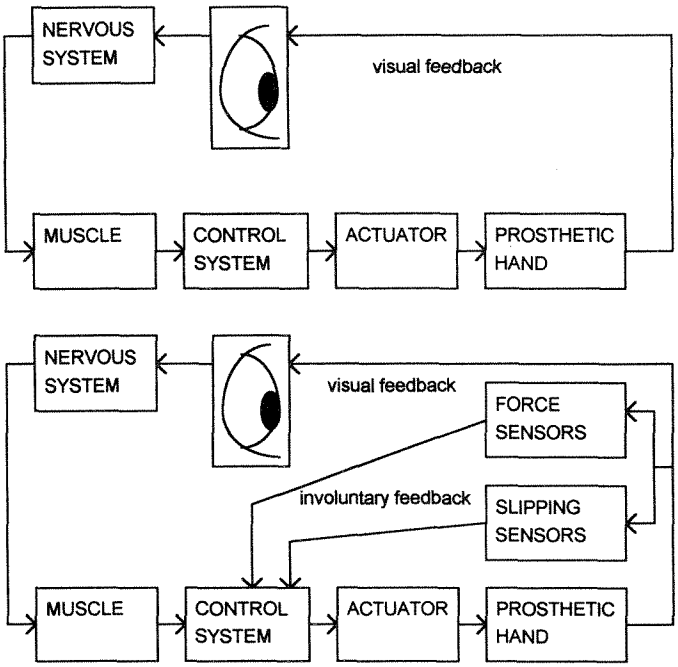

Figure 1.
Control system with visual feedback (top) and control system with involuntary feedback (bottom).

The Microcontroller Card for the Sensory Control System

To carry out the sensory control system for the Otto Bock hand, a microcontroller card was developed that processed the signals, both from the residual limb and from the sensors, to control the actuator of the hand.

The EMG signals from the residual limb are picked up by means of surface electrodes and processed by means of the following blocks:

1. Amplifier: gain 80 dB and sensitivity 10 μV.
2. High-pass filter: made up of condensers in series with the aim of eliminating the direct voltage (a component of noise, since it is not present in the original EMG signal).
3. Band-eliminating filter: it has the aim of reducing the network noise (50 Hz in Europe); it consists of a notch filter with a filtering effect of 45 dB at 50 Hz.
4. Double half-wave rectifier: the signal is rectified before being subjected to integration.
5. Integrator: integration corresponds to a low-pass type filtering with a cutting frequency of about 3 Hz.

The signal is then sampled at a frequency of 100 Hz, a rate found to be suitable on the basis of experimental tests. Finally, the EMG signals undergo a mobile average filtering, with a number of samples (D). The value of D can be set by means of software by linking a terminal to the microcontroller of the card. In this way, the global action of filtering can be modulated on the basis of the characteristics of the EMG signals of each user. Clearly, it is best not to oversize the value of parameter D, because that would make the user's control of the hand unnecessarily less prompt.

Originally, we had developed the card to carry out the proportional control system. However, since it was designed with a view to implementing new functions at a later date, only slight modifications were necessary to carry out the additional functions required by the sensory control system.

We used an Intel 87C196KC CMOS technology microcontroller, with various peripheral units incorporated: a PWM signal generator, two timers, a serial port, and an A/D converter with eight input channels.

The other main blocks of the card are as follows:

1. *Power Stage.* A DC/DC downhill converter with high performance that provides the motor of the hand with a voltage that varies between 0 and 7.2 V. The switching network of the converter consists of an H bridge made up of four power MOSFETs (two n-channel and two p-channel). The LC filter, normally present between the switching network and the load, is here carried out by the load itself: the high inertia of the motor and the windings of the stator and the rotor are, respectively, the equivalent of a capacity and an inductance.
2. *EEPROM Memory.* In addition to the EPROM of the microcontroller, where the executable operation code of the hand, the same for all persons, is memorized, an EEPROM retains the optimal values of the individual parameters of the prosthesis. To enable the prosthesis to work as well as possible, the values of the parameters must be chosen for each person (besides, even for the same person, the optimal values can vary in time, or simply according to the task that he or she intends to carry out with the prosthesis); these can then be set by means of software.
3. *Comparator for Revival from Power-down.* The power-down mode of the microcontroller is aimed at guaranteeing energy saving. This state is assumed if EMG signals are not picked up for a

certain period of time. The comparator for revival from power-down is an adder whose output goes high if the sum of the two EMG signals goes beyond a threshold (that can be set with a potentiometer). The output is connected to an external interrupt pin of the microcontroller, whose leading edge "revives" the micro from power-down.

4. *Voltage Regulator.* The voltage regulator is a DC/DC converter that, supplied with 7.2 V, provides the nominal output of 5 V, necessary for supplying the microcontroller. This current then undergoes low-pass filtering to obtain a voltage that is as constant as possible, in order to guarantee that the A/D conversion operations take place correctly.
5. *LEDs.* Two LEDs have the functions of signaling, respectively, the power-down state and the low battery state. When the card is applied to the prosthesis, the LEDs are positioned beneath small holes in the cradle, so that the client can see them.

The need to limit the size of the microcontroller card (for obvious problems of space) has led to choices that are not convenient for setting up and developing the system, both the hardware and the software. In fact, to satisfy very low amputation levels (wrist disarticulations), for which the space inside the prosthesis is very limited, a card with 6-layer SMD technology was developed (33×26 mm, 9 g), a size that makes hardware modification practically impossible. Moreover, again with a view to miniaturization, the socket for the components (and thus also for the microcontroller) was eliminated, precluding the use of the emulator for debugging the software. These limitations made it necessary to develop another card with traditional technology, with components on a socket and with the possibility of using an external EPROM instead of the one inside the microcontroller. This card is useful for testing the software by means of an emulator. Moreover, while in the SMD card the unused pins are linked to mass or to the power supply, in this card, all the pins are available, making possible the development and trial of new operations.

The software is structured on a set of starting procedures and a set of procedures that are carried out cyclically. The cyclical part of the program carries out the following tasks:

1. *Management of Communications with a Terminal or PC.* Serial communications in 8-bit asynchronous mode are activated by means of an interrupt every 100 msec. This enables the operator to set the values of the parameters of the prosthesis, and to see on the display how the EMG signals, the sensor signals, and the control signals (e.g., the battery charge level signal) vary in real time.
2. *Management of the Power-down State.* If a "muscular inactivity counter" reaches a certain value, the system goes into the power-down state to prolong battery life. All the interrupts are switched off, except the one that makes the system come out of this state.
3. *Power Supply Control.* It is necessary to make sure that the voltage remains above a safety threshold (5.6 V), to prevent the microcontroller from carrying out unexpected actions. Actually, the battery is considered to be insufficient only if voltage is found to be under the threshold for a certain consecutive number of samplings. This is to avoid the system being blocked by a temporary voltage drop due to an absorption peak of the motor. If the battery is found to be insufficient, the automatic opening of the hand is ordered and the microcontroller is blocked.
4. *Management of EMG and Sensor Signals.* This task is the heart of the program; it is effected by means of a routine activated by an interrupt every 10 msec. On the basis of the value of the EMG signals, the sensor signals, and some parameters, this routine activates the actuator according to the control law discussed below.

The Force-Sensing Resistor Sensors

The sensory control system is based on the use of force-sensing resistor sensors (FSR: Interlink Electronics, Santa Barbara, CA) made up of two thin leaves of polymer (0.2 mm in all), one of which is covered with a network of interlaced electrodes, while the other is covered with a semiconductive material. When no force is applied, the resistance between the electrodes is high; when a force is applied, the semiconductive material comes into contact with the electrodes, creating a short circuit area that determines a drop in resistance. The extension of the dynamic range of resistance (dR/R) is high (from 2 KΩ to 1 MΩ), and this enables the use of a simple and economic electronic interface, unlike other force sensors (extensometers, for example, have a low dR/R and require bridge circuits not necessary for FSRs). The interface used is, in fact, a simple opera-

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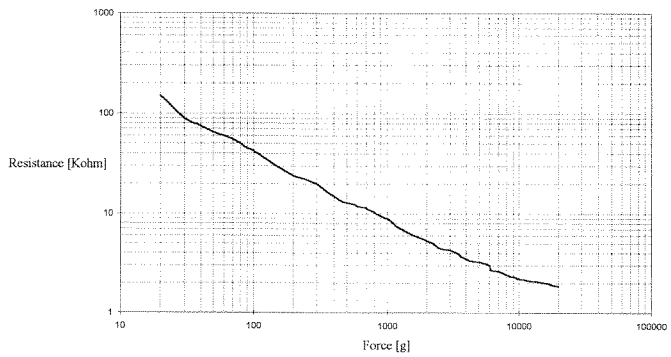

Figure 2.
Resistance/force static characteristic for a circular FSR (diameter=2.54 cm).

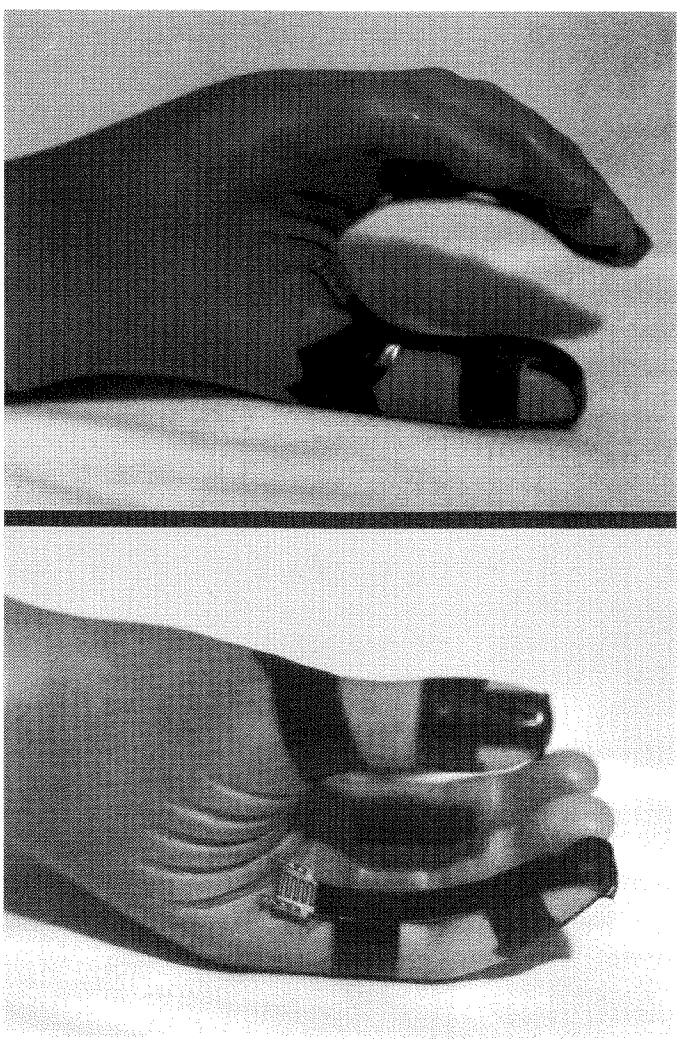

Figure 3.
Position of the strip FSR on the thumb (top) and on the index finger (bottom).

tional amplifier in nonreversing configuration, with gain that can be set by a potentiometer. Moreover, the force-resistance characteristic is very regular, since it is almost perfectly logarithmic. We have tested this on a circular force sensor of 2.54 cm diameter. Increasing loads were applied to this sensor by means of a cylindrical metal probe with a diameter of 1.27 cm. The characteristic obtained by interpolating the experimental points is shown in **Figure 2.** Clearly, the regularity of the characteristic is valid in a certain range of applied force: for very high values of force the curve tends to a saturation value, and for very low values of force it tends to increase rapidly. The sensitivity is expressed by the manufacturer in terms of pressure: 0.007 Kg/cm^2. This value is even higher than the requirements imposed by our application. The repeatability performance was also found to be satisfactory: we measured variations of ± 5 percent after 10 million activations.

The FSRs are available in various shapes and sizes; for the application on the prosthetic hand, we tested the 80×13 mm strips and the 5×5 mm squares. The former have the advantage that only one element determines a uniform region of sensitivity along the whole finger where it is applied. The latter have been found to be slightly more sensitive; however, at least three connected in parallel are necessary to obtain a sufficiently uniform sensitivity along the finger. This makes installation more complicated and gives the system a lesser degree of reliability (the presence of three or more sensors requires a higher number of electrical connections subject to wear and tear owing to their position). It should be noted that it is important to have the largest possible region of sensitivity along the fingers and not only at the fingertips (as is the case of the MARCUS hand); since the Otto Bock hand has only one DOF, grasping an object does not necessarily entail contact with the fingertips.

The FSR sensors have been placed on the thumb and index finger of the underglove. In order to obtain a good fastening of the sensors, we filed some parts of the underglove to make flat contact areas. Then the sensors were attached with cyano-acrylate glue and further secured with adhesive tape. To ensure good fastening, the strip sensors were shortened to 7 cm (this does not cause functional problems) and the edges were cut a width of 8 mm (except at the end with the contacts, which was left to its original width); it is possible to do this, since the width of the sensitive part is only 6.5 mm (**Figure 3**). Finally, the sensors were covered by the

cosmetic glove, to make them invisible on the outside; in this way the appearance requirement was fulfilled.

The "Intelligent" Hand: Automatic Touch

An innovation of the proportional control prostheses fitted at the Centro INAIL is the automatic research for contact with objects: an EMG signal impulse generated by the contraction of a muscle in the residual limb is sufficient to obtain the automatic grip with a certain strength. On receiving this impulse, the hand begins a closing action and goes on closing until the FSRs produce a signal that is greater or equal to a "contact threshold" value, and then it stops, since the object has been grasped with the required strength of grip. In brief, the user only gives the "start" order of the grip action, after which the latter occurs automatically without calling further on the user's will.

By the connection between the PC and the microcontroller, the parameters on which this function of automatic grip depends can be set in order to optimize the behavior of the prosthesis according to the user's requirements.

The most important parameters concerning this function are:

1. d = the number of samples for mobile average filtering on the FSR signals.
2. $n1$, $n2$ = the offset to subtract from the FSR signals of the thumb and the index finger, respectively.
3. T = the contact threshold, the force value theoretically reached in the action of automatic touch.
4. a = the duration of the opening impulse of the actuator in the final phase of the action searching for touch.

Regarding the last item, the inertia of the prosthetic hand is such that it does not stop immediately at the instant the power supplied by the actuator is set to zero. Thus, the contact threshold set for automatic touch is regularly exceeded. To limit this inconvenience, it was found to be useful to provide the hand with a "braking impulse": as soon as the FSR signals reach the contact threshold, instead of zeroing the power, a short opening impulse is supplied, and the power is only subsequently zeroed.

Once contact with an object has been reached automatically, the user can further increase the strength of the grip by activating the flexor muscle again. The prosthetic hand goes into the "squeeze" state and starts to work again according to the proportional mode. It should be emphasized that a parameter enables the choice between linear proportionality and square proportionality, because there are different opinions concerning the type of law that best correlates the effort of a muscular contraction with the EMG picked up. The diagram of the complete functioning of the prosthetic hand is shown in **Figure 4.**

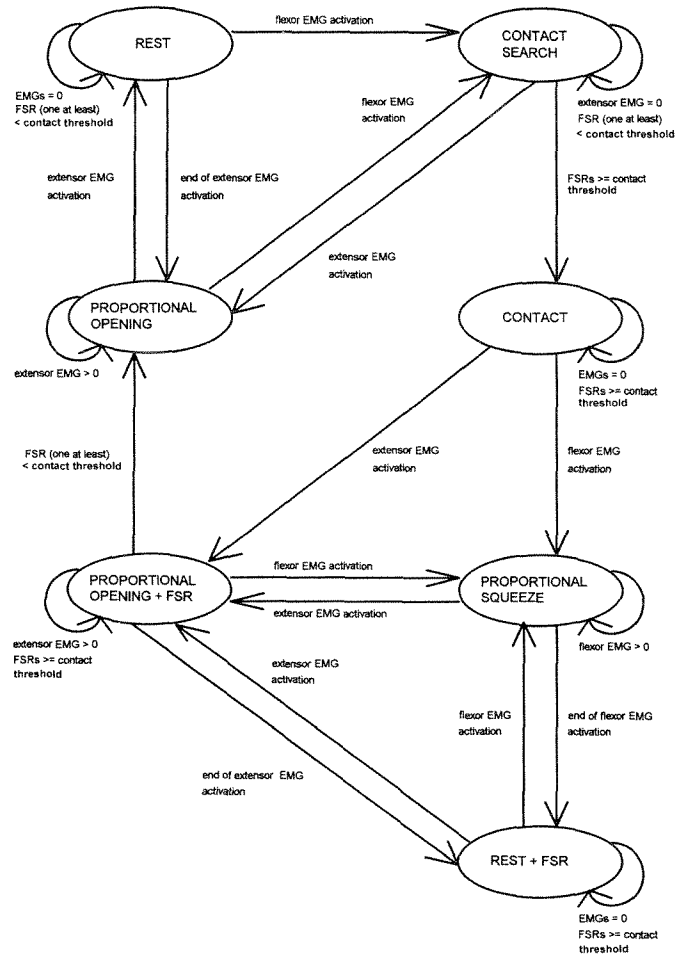

Figure 4.
Operation diagram of the sensorially controlled hand.

The Slipping Problem: an Optical Sensor for Motion Detection

Grasping delicate objects is obviously what users find to be most problematical, so the automatic grip mechanism becomes particularly useful in this circumstance; in order to avoid damage to these objects, it is necessary to set a low grip-strength value (i.e., a low value for the contact threshold). This can allow the

slipping of objects weighing more than a certain amount, depending on the intensity of the grip.

The problem can be solved if the user orders a further closing of the hand, once the automatic grip has been reached and found to be insufficient. However, the realization of a feedback control that is really involuntary entails the necessity also to automate any possible increases in grip strength, an objective that can be reached in this case by making use of information from one or more slipping sensors.

Bearing in mind the constraints of respect for appearance and size, the detection of slipping is not an easy problem to solve. The sensors taken into consideration were:

1. velocity Laser-Doppler sensors without contact, distance sensors without contact of ultrasonic, capacitive, and optoelectronic type
2. a vibration sensor (a piezoceramic bimorphic element) with small dimensions (15×1.5×0.6 mm)
3. an optical sensor with analogic memory for motion detection.

The first group of devices was discarded for problems of size and/or measurement field, and the second was discarded for problems of fragility; only the third was thought capable of providing reasonably good results.

The device, code named DIDI, is a 64×64 pixel image sensor with an analogic memory for detecting movement. It was developed at the Institute for Scientific and Technological Research (IRST) in Trento (Italy). It is an integrated circuit based on standard CMOS technology, in which the sensitive element consists of a matrix of photosensors fitted with an analogic memory that records the signal of the previous frame. It needs no specific light source, since it works with the light in the environment.

The cells of the sensitive matrix, each of which has a photodiode and a memory capacity, are directed by means of a line and a column decoder; the selection of the various cells occurs line by line. A series of switches connects the selected cell to the input of a motion processor that includes a charge amplifier and an analogic subtracter. This processor calculates for every cell the difference between the charge value provided by the photodiode (current frame) and the value memorized in the memory capacity (previous frame), after which it memorizes the former in the memory capacity. Finally, there is an output buffer that generates the actual output signal, an analogic signal giving the information of the difference, pixel by pixel, between the current frame and the previous one (**Figure 5**).

In order to function correctly, the sensor needs to receive a certain number of signals. These signals are the clocks for the counters (they enable and reset signals for the decoder), four non-overlapping phases for the motion processor, and a set of reference voltages for

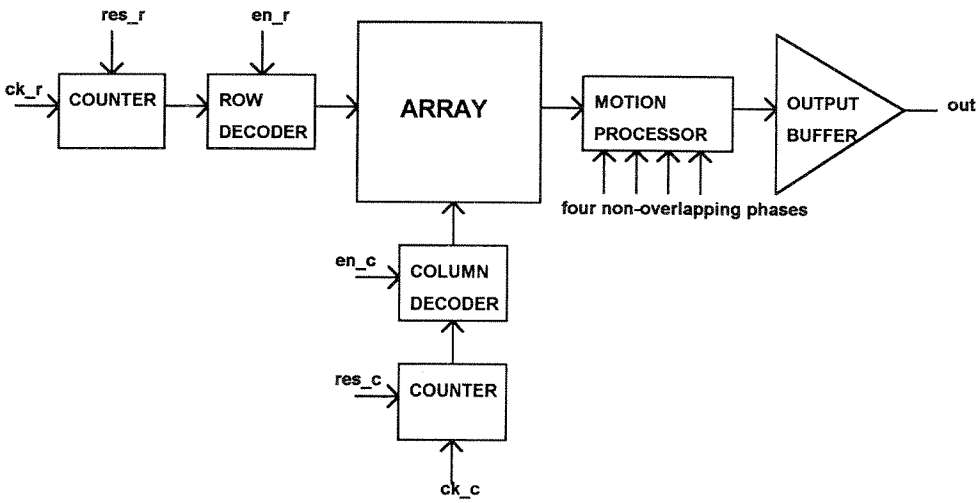

Figure 5.
Outline of the principle of the optical sensor DIDI.

both the processor and the output buffer. The voltages are provided by means of simple resistive dividers, while the above-mentioned signals are generated by a programmable logic circuit (the Xilinx XC3042 PC84C) that, when the system is switched on, is programmed by means of an EPROM in which the configuration program is situated (12–14).

The output signal has a theoretical constant value equal to 2.5 V in the case of a still image, while it has peaks in the case of a moving image (**Figure 6**). Each peak refers to a pixel of the sensitive matrix and the amplitude is proportional to the degree of light variation in time, so that positive peaks are obtained if the light increases and negative ones in the opposite case.

According to the above considerations, it is clear that if it were possible to position the sensor on the prosthetic hand in such a way as to frame the object during the grip phase, it would be possible to detect any movement, evidence of the beginning of slipping: the sensor, on framing a moving image, would give rise to peaks on the output signal.

In order to use the information obtained, it is necessary to manage the output suitably. Two stages of signal processing are located after the sensor: a precision rectifier and a time integrator. The first is required for obtaining peaks of the same sign, so as to avoid peaks of different signs compensating for one another: both positive and negative impulses are, in fact, evidence of a moving image, so both must contribute to the increase of the output of the integrator and not cancel each other out. The integration time is equal to the duration of a frame: at the beginning of a new frame, the output is reset to ground, and immediately afterward a new cycle of integration begins. The output of the integrator referring to the generic i-th frame provides global information about any possible variation between the frame itself and the previous one. At this point, information that can easily be used is available; the microcontroller samples this signal and compares it with a threshold: if the former is found to be higher, that is evidence of slipping, and the order is given to increase the intensity of grip on the object. The power assigned to the motor is the maximum: it is necessary to intervene in time by increasing the strength of the grip to stop the object from falling. The hand must, of course, already be in the grip phase (both the FSR signals are greater than zero), and no EMG signals must be picked up: if they are present, they determine the behavior of the prosthesis, since they are the expression of the user's explicit wish to carry out a certain action, whether a slipping situation is present or not.

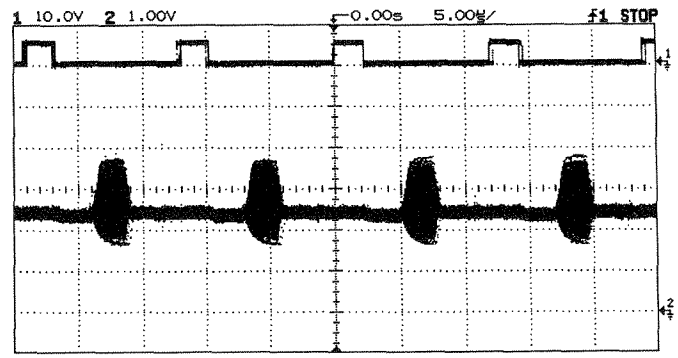

Figure 6.

DIDI output in presence of movement, captured with the storage function of the oscilloscope (midline); a phase of the motion processor (top).

The DIDI is not capable of effecting the perfect subtraction between the image at time i and that at i-1, so when there is no movement, its output does not maintain a perfectly constant value at 2.5 V (2.5±0.2 V). This influences the later stages; in particular, it causes the integrator output to vary from 2.5 V; it increases to a certain value that depends on the time-constant RC of the integrator itself.

It is therefore necessary to choose a compromise: to avoid an output that is rapidly saturated even when there is no movement, it would be better to choose a high RC; on the other hand, this choice leads to a reduction in sensitivity in the presence of a meaningful signal. Experiments carried out with varying values of RC have not led to acceptable results, so it was decided that an Rr resistance should be placed in parallel with the capacitor; in this way, even with a small RC, in rest conditions the output has a limited increase. While the capacitor is charged, it is able to partially discharge through the Rr; on the other hand, since it is possible to choose a sufficiently small RC, in at least a few instants of the integration cycle the variation of the output in the presence of a moving image remains satisfactory. Clearly, the behavior of the output is no longer ramp-like; in rest situations, the output appears as it does in **Figure 7** (top).

The value of the plateau reached by the output depends not only on RC and Rr, but also on the level of environmental light. We therefore found it convenient to carry out a procedure for self-learning the "slipping

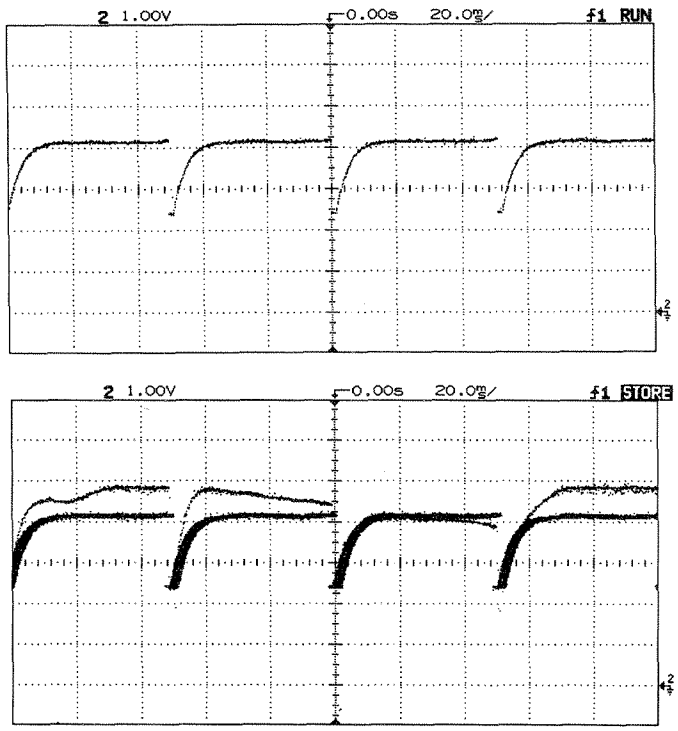

Figure 7.
Integrator output in absence of movement (top) and in presence of movement (bottom).

threshold'' (i.e., the value of the plateau), to avoid searching for it manually by interacting with the microcontroller by means of the PC. The procedure samples the signal 20,000 times (in about 3 s) and then calculates the mean value (that is found to be reliable with this number of samples); this mean value is then multiplied by a corrective value greater than one; the resulting value is the slipping threshold. At present, this routine is carried out when the system is switched on or reset.

In the presence of movement, the signal is deformed in a somewhat unforeseeable way, so that it is not certain that the maximum is reached at the end of the integration cycle (**Figure 7,** bottom); as a result, it is not sufficient to sample immediately before the reset instant: it is necessary to have sufficiently dense sampling during the whole integration cycle.

RESULTS AND DISCUSSION

The tests described below were carried out using a male hand fixed on a metallic support. A hand that consisted of all new components (mechanical part, underglove, cosmetic glove) was chosen.

The aim that was initially defined was to search for a parameter set that enabled the most delicate grip possible.

One of the first problems encountered in searching for this optimal set was the variability of the offset of the FSR signals with respect to the openness of the hand: the FSRs give rise to a signal that is greater than zero even in the absence of grip, because of the pressure of the adhesive tape used to attach them and of the cosmetic glove, and also because they are slightly curved to match the curvature of the fingers. If the offset were constant, we could easily compensate for it by means of the parameters of offset subtraction, *n1* and *n2*. But the variability of the offset with respect to the position of the fingers, owing to the fact that the degree of curving of the sensors depends on this factor (in the part of the sensor corresponding to the base of the fingers) forces us to choose high values of *n1* and *n2* on the basis of the worst case. This entails a decrease in the sensitivity of the sensors corresponding to the positions of the hand characterized by lower offset of the FSR signals. The more closed the hand is, the greater the offset, because the sensors are more curved in the area around the base of the fingers. This spatial variability of the offset is about 30 percent. There is also a temporary variability of offset, although it is less pronounced: even with the hand closed in a certain position, the offset oscillates continuously (about ± 5 percent around the mean value). This variability also depends on the gain of the FSR signals (that can be set by means of a potentiometer), forcing us to limit the amplification. The variability can, on the other hand, be limited by selecting a high value for parameter d (number of samples of the mobile average filter on the FSR signals); however, this means the microcontroller is less rapid in recognizing that contact with the object has been reached. In fact, it has been found experimentally that an increase in d leads to two effects that compensate for one another, leaving the situation practically unchanged. Since any action on d is not a useful strategy, it is left at the default value (d=1) or at the most d=2.

In practice, the problem of the variability of the offset of the FSR signals concerns only one of the two sensors. We realized that it is possible to make contact with an object dependent on only one FSR signal. This could create problems when the thumb and the opposing fingers do not reach an object at the same time: the hand could stop before it had actually touched the object. However, this case is purely theoretical: the

sensitivity of the sensor, once the offset of the worst case has been subtracted, is not sufficient to cause activation in the absence of a suitable resistance from the object, and the resistance is sufficient only if the opposing fingers have also come into contact with the object. We decided to make the touch depend on the thumb FSR, since the thumb must be involved in gripping any object; on the other hand, since there are four opposing fingers, grip could occur without, for example, the index finger being involved. The sensor on the index finger has not been eliminated, since it has taken on a different function: checking the maximum strength applied to an object during the state of proportional squeeze. The threshold value of maximum strength is also a parameter that can be set by means of the software. The FSR signal of the index finger is amplified much less than that of the thumb: for the function it carries out, great sensitivity is not important; on the contrary, it must not go into saturation at low strength values.

When the strip sensors (7 cm length) are used, the set of values that determines the most delicate grip possible is the following:

$$d = 2$$
$$T = 1$$
$$n1 = 248$$
$$n2 = 0$$
$$a = 2$$

All these parameters have a range from 0 to 255. Their setting was obtained by trial and error, measuring the strength of the automatic touch with a dynamometer. The minimum value of strength obtained was 2 kg.

For the reasons given above, no offset was subtracted from the FSR signal of the index finger ($n2$=0). On the other hand $n1$ is high because the FSR signal of the thumb was highly amplified, to have as great a sensitivity as possible.

The contact threshold T is set to the minimum value.

The braking impulse is equal to $2 \cdot \Delta t$, with Δt of 130 ms. Braking cannot be too long; otherwise, the hand can actually carry out an opening movement, with the object falling from the grip as a result.

We have tested the contact with everyday objects of various shapes, sizes, and low mechanical resistance (plastic bottles, pieces of fruit, glasses, and so forth). The grip is such that these objects are not damaged. However, objects even more delicate, such as eggs and paper cups, were broken.

To obtain a still more delicate touch, we decided to shorten the sensor on the thumb from 7 cm to 5.5 cm. This lessens the problem of the degree of bending of the sensor that varies with respect to the position of the fingers, and so reduces the variability of the offset of the signal, enabling the sensor itself to have greater sensitivity.

This shortening of the sensor has the disadvantage of reducing the sensitive surface; however, the length remains sufficient to cover the thumb from tip to base. The whole palm of the hand is not covered, but it is rather unlikely that the grip of an object involves only this part of the hand. In this new sensor arrangement, $n1$ can be reduced to 150 (while the other parameters keep the same values). The minimum strength obtained is now 0.6 kg.

In the following, results of the touch trials with light (<150 g) objects and with objects of low mechanical resistance are described in detail. For each object, 10 touch trials were carried out, varying the area of contact of the hand with the object (as happens in reality). In all the trials the hand started from an opening of 5 cm between the tips of the thumb and the index finger.

1. *Empty Cardboard Box (20 g):* in four trials the deformation was not negligible; in the other six cases the deformation can be considered acceptable.
2. *Single-dose Oven Product (40 g):* considering the high level of crumbliness, the deformation can be considered to be acceptable.
3. *Empty Half-liter Plastic Bottle (30 g):* the object never underwent significant deformation.
4. *Tube of Mayonnaise (160 g):* the object never underwent significant deformation; since it was heavier than the previous objects, it began to slip three times, but stopped owing to its surface not being perfectly smooth.
5. *Banana (120 g):* the object never underwent significant deformation, but it slipped and fell from the grip twice.
6. *Raw Egg (70 g):* in this case, the object was never broken or cracked.

The limit is still found to be paper cups: these regularly undergo significant deformation. The results of some automatic grips on these objects are shown in **Figures 8** and **9.**

The set of trials described was repeated using square 5×5 mm sensors (three in parallel on the thumb).

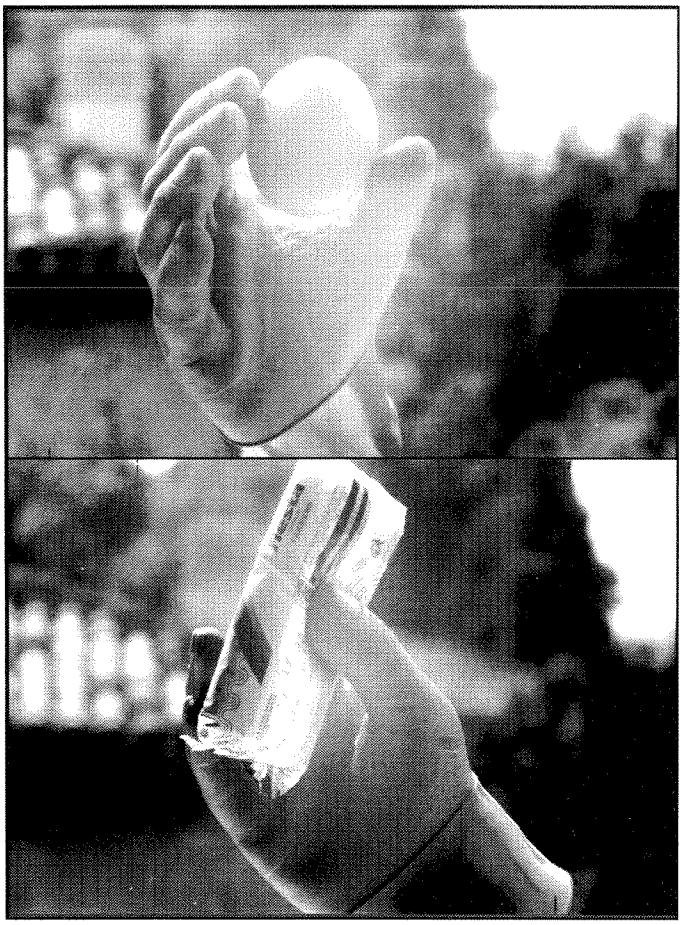

Figure 8.
Automatic grip of delicate objects: egg and snack.

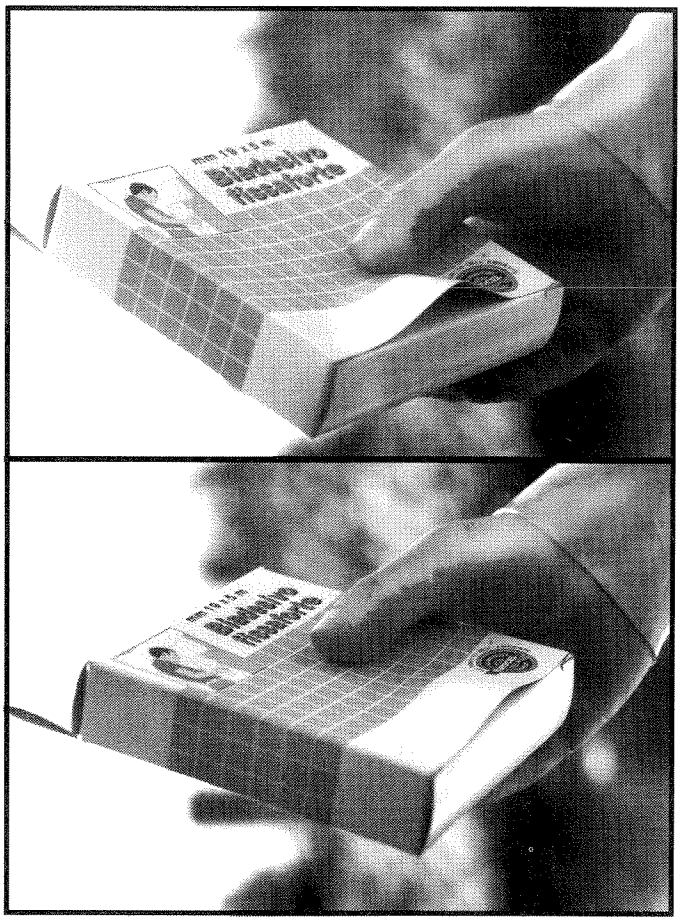

Figure 9.
For some objects, the quality of the grip depends on the position of the contact area.

The results were slightly better, but we do not think this justifies the greater constructional complexity and the lower reliability of this configuration.

From these trials, it can be deduced that the choice of the minimum contact threshold enables even delicate objects to be gripped without damage, but on the other hand, the heavier the object is, the more it tends to slip. However, weight is not the only factor that determines the tendency of the object to slip, as became clear in other trials on heavier and larger objects, in which the hand started from the maximum degree of opening, but with the same parameter values. The most significant case in these trials was the grip of an orange with a very porous surface: though weighing 300 g, it never slipped from the grip, nor even began slipping, unlike objects that were only about 100 g, but with smoother surfaces, such as the banana reported above. The extension of the area of contact between the hand and the object also has an important role: when the other factors are the same, a larger extension is an obstacle to slipping.

Therefore, in the absence of a slipping sensor, the choice of the value of the contact threshold for automatic touch is a compromise between two requirements: 1) gripping delicate objects without damaging them (low contact threshold) and 2) preventing heavy objects from slipping (high contact threshold).

When a slipping sensor is included, it is possible to set the contact threshold to the minimum value (without considering the type of objects to be manipulated), since the slipping sensor automatically increases the grip if necessary.

As far as the slipping sensor DIDI is concerned, it should be pointed out that up to now it has not been possible to carry out tests with it actually installed on a prosthesis. In fact, up to now we have only carried out a

demonstration system based on a master card the size of which was not suitable for installation on the prosthesis. However, the dimensions could be drastically reduced as follows:

1. The sensor is now a 40-pin chip, but it is possible to replace it with a 28-pin package.
2. The Xilinx used is an 84-pin device, but the system does not use all its potentiality; a device with fewer logic units and therefore of a smaller size (about a fourth of the former one) could actually be employed.
3. Instead of a 28-pin parallel EPROM, an 8-pin serial EPROM could be used.
4. The test card was designed with the aim of constructing a demonstrator, with no attention paid to problems of size; moreover, it was not created ad hoc for DIDI, since it was also used for other devices.

In other words, by designing a card ad hoc in SMD technology, the whole system could be placed inside the cradle of the prosthesis. The sensor should then be connected to a coherent optic fiber capable of transporting images, one end of which would be placed facing the area of interest (that is, the area of hand-object contact). To do this, it would be necessary to open a small hole in the cosmetic glove, so as to enable the fiber to "see" the object gripped: this is undoubtedly a disadvantage, but not something that would seriously damage the appearance.

The tests so far were carried out in environments where the luminosity varied between 175 and 1400 Lux. They consisted of moving objects of various shapes, sizes, and colors within the visual field of the sensor, so as to simulate manually the movement condition of an object owing to an insufficient grip strength, to see if the hand automatically carried out a closing movement in such a situation.

The best results were obtained by assigning the following values to the parameters concerning the management of slipping:

1. parameters of the integrator: RC=190 μs, Rr=22 KΩ
2. corrective factor for the self-learning procedure of the slipping threshold: CF=1.07.

With this set of parameters, it was observed that the slipping signal (the output of the integrator) in the condition of lack of movement is characterized by a plateau with oscillations lower than 4 percent with respect to the mean value; on the other hand, when there is movement, the signal increases with respect to the mean value of the signal at rest up to values 20 percent higher. This enables even slight movements (between 1 and 5 mm) of all the objects tested to be detected (both movements in the orthogonal direction and in the tangent direction to the plane of the sensor). However, it was found that the sensor showed greater sensitivity in recognizing objects of a dark color. With this setting of the parameters, false positives (that is, erroneous recognition of a slipping condition) did not occur.

It has not yet been possible to carry out clinical tests on a large scale; in any case, they have only concerned the automatic touch function, since it is not yet possible to install the slipping sensor on the prosthesis.

The first volunteer was a male, aged 45, with a third-mean right transradial amputation. Before trying the automatic touch function, it was necessary to spend a long time on training the subject (it was the first time a myoelectric prosthesis was applied) and on setting the parameters that influence the management of the EMG signals. Initially, he was not able to activate the two muscles (flexor and extensor) independently; or rather, in the attempt to activate the flexor, an extensor signal higher than that of the flexor was obtained for the same amplification. Once these problems were solved, the subject only had time to carry out a few automatic touch trials: sitting down, he managed to grip some of the previously mentioned objects arranged on a flat surface.

Fewer problems were encountered with the second subject, a male, aged 35, with a disarticulation at the right elbow. The muscles used in this case are the biceps (closing) and the triceps (opening). This subject was able to try out the prosthesis for a whole day, carrying out various activities (including lunch).

Both subjects showed that they immediately understood the control philosophy behind the "intelligent" hand, and they particularly appreciated the lower degree of attention necessary for using the prosthesis. They both expressed the desire for an automatic increase in grip when an object slips.

As soon as the sensor system has been perfected (as already stated, the management of slipping still requires a great deal of work), a series of clinical trials will be undertaken on a greater number of subjects, giving them the possibility of trying the prosthesis in their own homes.

CONCLUSION

A system of sensory control has been developed for an Otto Bock hand prosthesis. The sensory control system consists of two main functions:

1. the automatic search for contact with the object
2. the detection of the object possibly slipping from the grip.

The first function, based on the use of FSR sensors, has already reached a satisfactory level of development. However, an important improvement is still possible: the manufacture of a cosmetic glove in silicone with the FSR already in it. In this way, presumably it will be possible to obtain a more delicate automatic touch than that which can be obtained at present (it is not yet possible to hold a paper cup without damaging it).

The advantages of automatic touch can be summarized in the following points:

1. it frees the user from the need for visual control during the grip action.
2. it lessens the risk of damaging delicate objects (especially in persons new to prostheses, this risk exists even if the action of the prosthesis is followed visually).
3. it increases the speed of the grip: since grip is automatic, the actuator can be given maximum power, thus maximum speed (actually, this advantage also is clear to persons new to prostheses, less for those who already have some experience in using prostheses).

The development of a device managing slippage still requires a great deal of work in order to miniaturize the system for installation on the prosthesis. On the other hand, only the integration of the two functions can give rise to a really efficient sensory control: in this way, not only does the contact with the object become automatic, but also, so does the increase in grip when the object starts to slip.

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