

# Sensory feedback in upper limb prosthetics

*Expert Rev. Med. Devices* 10(1), 45–54 (2013)

Christian Antfolk<sup>1</sup>,  
Marco D'Alonzo<sup>2</sup>,  
Birgitta Rosén<sup>3</sup>,  
Göran Lundborg<sup>3</sup>,  
Fredrik Sebelius<sup>1</sup> and  
Christian Cipriani<sup>\*2</sup>

<sup>1</sup>Department of Measurement  
Technology & Industrial Electrical  
Engineering, Lund University, Lund,  
Scania, Sweden

<sup>2</sup>The BioRobotics Institute, Scuola  
Superiore Sant'Anna, Pontedera, Pisa,  
Italy

<sup>3</sup>Department of Hand Surgery, Skåne  
University Hospital, Malmö, Scania,  
Sweden

\*Author of correspondence:  
[ch.cipriani@sssup.it](mailto:ch.cipriani@sssup.it)

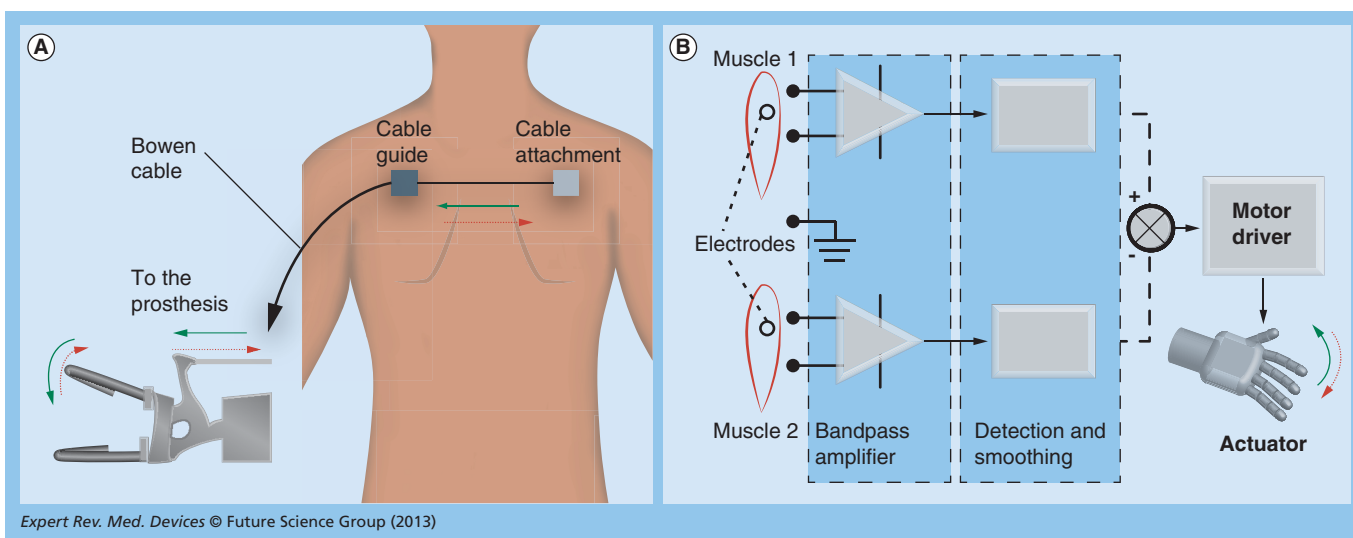
One of the challenges facing prosthetic designers and engineers is to restore the missing sensory function inherent to hand amputation. Several different techniques can be employed to provide amputees with sensory feedback: sensory substitution methods where the recorded stimulus is not only transferred to the amputee, but also translated to a different modality (modality-matched feedback), which transfers the stimulus without translation and direct neural stimulation, which interacts directly with peripheral afferent nerves. This paper presents an overview of the principal works and devices employed to provide upper limb amputees with sensory feedback. The focus is on sensory substitution and modality matched feedback; the principal features, advantages and disadvantages of the different methods are presented.

**KEYWORDS:** electrotactile feedback • invasive feedback • mechanotactile feedback • neural stimulation • noninvasive feedback • prosthetic hand • sensory feedback • sensory substitution • upper limb prosthetics • vibrotactile feedback

Losing a limb after amputation is a devastating event with the inevitable loss of both motor and sensory function, resulting in a disability with possibly enormous consequences for activities of daily living and quality of life [1,2]. The grasping function can be primitively restored using an active prosthetic hand, either a body-powered or battery-powered prosthesis. In body-powered prostheses, the person uses gross movements of his/her own body to control the prosthesis. A Bowden cable is used to transmit the forces developed by the body movements to a terminal device: either a split hook or a mechanical hand (FIGURE 1A). In technologically advanced battery-powered prostheses, electromyographic (EMG) signals from residual muscles are tapped through surface electrodes and electrically processed to functionally operate an electromechanical hook/hand with electrical motors (FIGURE 1B) [3]. While an acceptable level of grasping function is often gained through active prostheses, the restoration of sensory function remains one of the open challenges in this field, which contributes to preventing a wider acceptance and ease of use of these devices, as reported by surveys among amputees [1,2].

The control of grasping and manipulation largely relies on tactile feedback in humans [4]; hence, a common thought is that prostheses would function better if they used closed-loop control, making use of both exteroceptive, as well as proprioceptive information [5,6]. To achieve

this goal, the prosthesis should not only be able to detect physical interactions with the environment (i.e., exteroception) and sense the proper state like its joint angles (proprioception), but it should also be able to convey such information to the user in a perceivable and possibly effortless manner. Nowadays, none of the prostheses used in clinical practice have purposely designed closed-loop controllers. Control is achieved by the individual, by means of visual feedback and incidental stimulation (audition, socket pressure, harness, etc.) but not often through design intention. With body-powered devices, users can sense the prosthesis state and grip strength through the reaction forces transmitted by the control cable and harness on their skin/body. Even though this type of feedback is limited, it most likely contributes (together with the low weight and cost) to the choice of body-powered prostheses over myoelectric ones. Paradoxically, in fact, the more sophisticated myoelectric prostheses lack this sensory awareness that cable and harness attached to the body provide to the wearer; the user must rely on vision to regulate his or her activity with significant cognitive effort. However, technological improvements are making myoelectric robotic multifingered prostheses more reliable, and they may become more popular in the future, hence it is important to identify ways of providing feedback to the user of prosthesis state and grip strength.



Expert Rev. Med. Devices © Future Science Group (2013)

**Figure 1. Conventional powered prostheses.** (A) In a body-powered prosthesis, the movement developed by a body part (in this case bicipital abduction) is transmitted to the terminal hand/hook by means of a cable running into a guide (Bowden cable). The cable in turn transmits reaction forces from the hand/hook to the body, hence providing a sensory awareness of the prosthesis. (B) In a battery-powered myoelectric prosthesis, the signals recorded from antagonist muscles are processed to open/close the various degrees of freedom of the prosthesis. Besides incidental stimulation (motor sound, socket pressure and vibration), there is no built-in sensory feedback to the individual.

Various approaches to and designs of sensory feedback systems have been presented over the years, but none has yet been convincingly proven usable and, thus, been made commercially available. In this paper, the authors review the important features describing sensory feedback in upper limb prosthetics as well as summarize significant work carried out in the field. Since an exhaustive review cannot be accomplished here, the authors wish to apologize to those researchers engaged in important work that were not mentioned.

### Sensing information & feeding it back

Somatic receptors in the upper limb are divided in cutaneous and subcutaneous mechanoreceptors, muscle and skeletal mechanoreceptors, nociceptors and thermal receptors. This complex sensory system encodes and transmits, to the CNS, information about four major modalities: touch, proprioception, pain and temperature. After amputation, that is after the loss of receptors and interruption of the physiological channels, there are two potential ways to elicit sensory feedback: invasively, by interfacing directly to physiologically relevant neural structures in the peripheral nervous system or the CNS or noninvasively, by providing feedback to intact sensory systems (e.g., tactile stimuli on the residual limb, chest, etc.). In both cases, the subject should be trained to associate stimuli to physical events occurring at the prosthesis (exteroception) or to states of the prosthesis (proprioception).

The general architecture of providing sensory feedback could be described by four blocks in a cascade that comprise: sensing transduction, decoding algorithm, encoding algorithm and actuating transduction, as detailed in Figure 2. Body-powered prostheses represent a very simple yet smart example of the above scheme, in which the whole process is executed mechanically and the feedback

comes from the control interface, which is under direct control of the CNS. No signal processing is required and sensing/actuating transducers are substituted by mechanical couplings. Battery-powered myoelectric prostheses lack this sensory awareness, and sensory feedback can be attained and provided by means of sensors (for a review of sensors in artificial hands see [7]) and actuators. In a prosthesis interfaced to the afferent nerves through implanted electrodes [8], the actuating transduction block is likely to be an electronic amplification/conversion stage, like a voltage to current converter (e.g., [9,10]).

### Timing aspects

In addition to the sensory modality (what is fed back), another crucial aspect is the timing of sensory feedback (when it is fed back). The latency between a variation of the output stimulus corresponding to a sensory input variation should be as short as possible for an effective volitional use of such information. In the unimpaired human sensory system, tactile stimuli take 14–28 ms to reach the cuneate nucleus [4]. Therefore, it is reasonable to believe that to avoid increasing this value significantly, artificial sensory feedback should be delivered to the individual in a fraction of that time (e.g., 3–5 ms).

Short latencies are also important for the brain to develop a sense of embodiment (body ownership) of the prosthesis. Indeed, the attribution of a visible hand to the self depends on a match between the afferent somatic signals and visual (and eventually audio) feedback from the hand [11]. In order to attain self-attribution, temporal delays lower than 300 ms are required, as reported by Shimada *et al.* [12].

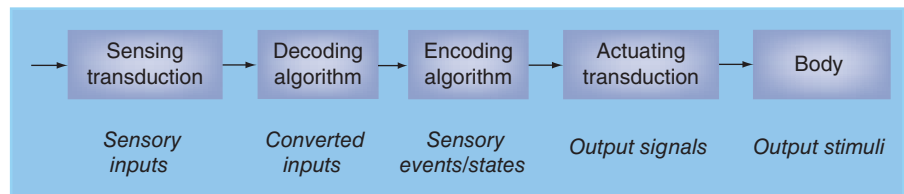
The prevalence of stimulation, that is how continuous sensory feedback is to be provided, is still a debating point within the field. Traditionally, researchers have implemented systems that presented the sensory feedback in a continuous fashion. However, continuous

sensory feedback leads to adaptation, meaning that the stimulation is no longer or it is barely perceived by the individual after a short while. This is especially true when sensory substitution (see paragraphs below) is applied and is likely to be caused by the fact that the brain interprets the feedback information containing little variation as irrelevant. Other approaches, like that proposed by Johansson and Edin [13], build on the fact that motor tasks in humans are organized by means of discrete sensory 'events' that delimit functional task phases (e.g., object contact, lift-off, etc.), and hence suggest that sensory feedback should be provided in a discrete sensory event-related fashion. They argue that although transferring such events requires good temporal precision, the bandwidth requirement is evidently much smaller compared with traditional solutions and no adaptation would occur.

### Closed-loop control

A prosthesis with sensory feedback can exploit the concept of closed-loop control [5]. Childress originally proposed the division of the sensory information from the prosthesis to the individual, into three pathways as shown in FIGURE 3 [14]. Pathway A consists of visual or auditory feedback signals that are present by default in all prosthetic systems. Users rely on viewing the terminal device (and experience gained with usage) while grasping an object, to roughly regulate the grip strength. Furthermore, incidental auditory cues like the sound produced when the hand/hook touches the object, as well as the motor sound (in battery-powered prostheses) while grasping are often exploited for control. Pathway B consists of somatic sensory signals (e.g., tactile, proprioception, temperature, vibration) which are directed either to the skin, or directly to the afferent nervous system. Incidental somatic signals like hand vibrations or pressures transmitted to the residual limb by the socket are also included in pathway B and seldom used for control. Pathway C consists of feedback that is intrinsic to the prosthesis control system, for example using sensors in the prosthetic hand to automatically adjust the grip force or to avoid slippage of objects.

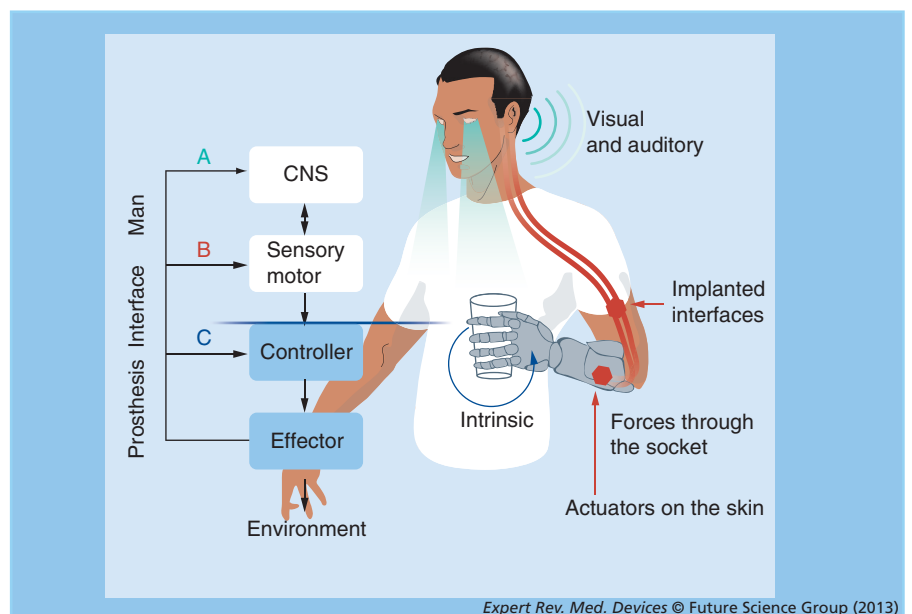
There are several sensor options possible for integration in myoelectric hands, capable of measuring a wide range of information like: contact, force, pressure, position, slip and temperature [7]. In commercial devices (like the Sensor-Hand, i-Limb, BeBionic [201–203]), sensors are used to automatically regulate the



**Figure 2. General architecture for providing sensory feedback.** The input stage, namely sensing transduction, converts physical stimuli (sensory inputs) from one form of energy (typically mechanical) to another form of energy (converted inputs, typically electrical) that is more appropriate for processing. Then, a decoding algorithm identifies important sensory events/states (e.g., contact or angular position of a joint), and an encoding algorithm transforms them into output signals that can be interpreted by the CNS as if they were a substitute of the sensory input. The output stage – that is, actuating transduction – converts the output signals into the appropriate form of energy to be applied on body sensory systems (output stimuli) either invasively or noninvasively.

grip force (pathway C in FIGURE 3) without having the user in the loop. As an example, in the newly marketed multifingered hands (i-Limb and BeBionic), motor current sensors are used to stall the different fingers independently, in order to achieve an adaptive grasp. Pathway C is important from the engineering perspective; it also resembles peripheral mechanisms existing in the natural unimpaired hand that prevent slippage of objects [15]. It seems reasonable that these processes should proceed without requiring directed attention (i.e., as automatic subroutines) in order to avoid interference with the overall goal of the manipulative task [5,14,15].

To enable the user to regulate the grip-force/joint position according to what is sensed, the loop needs to be closed through pathway B. In the following paragraphs, the authors describe



**Figure 3. Diagram of man-prosthesis system showing the three possible information pathways proposed by Childress [14].** Different colors correspond to different pathways. Pathway A (in light green) is related to sensory information directly fed back to the CNS, like visual and auditory feedback. Pathway B (in red) refers to sensory information conveyed to functional sensory motor systems either invasively or noninvasively. Pathway C related to the intrinsic feedback within the prosthesis is sketched in navy blue.

systems and techniques to implement pathway B that have been attempted by researchers.

### Sensory substitution feedback

Sensory substitution is a method to provide sensory information to the body through a sensory channel different from that normally used (e.g., substitute touch with hearing) or through the same channel but in a different modality (e.g., substitute pressure with vibration) [16]. Most of the feedback systems proposed for battery-powered upper limb prosthetics exploit this idea, due to the challenging task of restoring the physiologic sensory information when the original mechanoreceptors are no longer available. Prevalent techniques have been vibrotactile and electrotactile sensory substitution which uses either a mechanical vibration or an electric current presented to the skin in order to code information relative to the grasp, joint position or direction.

### Vibrotactile sensory substitution

Vibrotactile stimulation is evoked by a mechanical vibration of the skin at frequencies ranging between 10 and 500 Hz [16]. The two main features of the stimulus are vibration amplitude and frequency, but other features like pulse duration, shape and duty cycle can be modulated to convey different kinds of information [17,18]. The amplitude discrimination threshold depends on several parameters, including the frequency and location on the body. Lower thresholds are found on glabrous skin as compared with hairy skin and at frequencies in the range 150–300 Hz. Highest thresholds are found in the abdominal and gluteal regions (4–14  $\mu\text{m}$  at 200 Hz), whereas lowest thresholds are measured on the fingertips (0.07  $\mu\text{m}$  at 200 Hz) [19].

In prosthetics, vibrotactile feedback was firstly proposed by Conzelman *et al.* in 1953 [101]; since then it has been explored due to its compatibility with EMG control and higher acceptability compared with electrotactile stimulation [16,20]. Bach-Y-Rita and Collins proposed concepts where arrays of vibrotactile stimulators would convey proprioceptive information on the back or on the residual limb of the amputee [21]. Mann *et al.* detailed a system where the elbow angle of the Boston Arm was fed back exploiting vibrotactile stimulators [22]. Early devices were quite bulky and power consuming. Today's vibrators can be low-power, unobtrusive and potentially embeddable within the socket [17,23,24]. In recent years, vibrotactile systems have been used in research with the Otto Bock, Motion Control and i-Limb myoelectric prostheses [24–26], and with the Cyber- [27], MANUS- [28], Fluid- [29] and Smart- [23] hands. Generally, the use of vibrotactile feedback improves user performance through a better control of grip force and by lowering the number of errors in task execution. However, a comparison between direct haptic feedback (force) and vibrotactile feedback showed that task execution time was lower with direct feedback [30].

### Electrotactile sensory substitution

Electrotactile (or electrocutaneous) stimulation evokes sensations within the skin by stimulating afferent nerve endings through a local electrical current. The sensation is not necessarily confined to the zone under the electrodes but elicited sensations could spread if these

are placed near nerve bundles [16]. Electrotactile stimulators can be designed to be either current- or voltage-regulated. With current-regulated stimulation, the current is not affected by changes in the tissue load and impedance at the electrode interface; on the other hand, voltage-regulated stimulation minimizes the possibility of skin burns owing to high current densities. Current amplitude, pulse waveform (biphasic/monophasic, rectangular/sinusoidal), pulse frequency and duration, and duration of pulse bursts are the principal features of the stimulation. Typical currents range within 1–20 mA, with pulse frequencies ranging from 1 Hz to 5 kHz; biphasic pulses produce more comfortable sensations compared with monophasic pulses [31]. Saunders reported that the average threshold charge for pulses repeated at 60 and 200 Hz was 62 nC, and that this value was constant across a range of current amplitudes (1–20 mA), pulse durations (1–100  $\mu\text{s}$ ), and frequencies (60–200 Hz) [32]. Subjects described electrotactile sensations qualitatively as a tingle, itch, vibration, touch, pressure, pinch, and sharp and burning pain depending on the stimulating voltage, current and waveform, as well as on the electrode size, material and contact force, and the skin location, hydration and thickness [16]. Typically, electrotactile devices consume less power and respond faster than vibrotactile systems as there are no moving mechanical parts. The main drawback is interference with myoelectric control when the stimulation sites are close to the EMG electrodes; frequency or time multiplexing techniques have been investigated to address this pitfall [33,34].

In prosthetics, several researchers investigated ways to convey grip or position information by modulating the amplitude of the pulses [35], the frequency [36] or the rate of pulse bursts [35,37] to a single or multiple [38] stimulation sites. Amplitude modulation was shown to be superior to pulse rate modulation in conveying grip intensity, however pulse rate modulation was less susceptible to adaptation [16]. Electrodes with a small area are required when only a limited area is available; however larger electrodes provide a more comfortable sensation [16]. Hence, a trade-off between electrode size and skin area should be identified when performing multisite stimulation.

### Other sensory substitution principles

Other sensory substitution principles have been employed to provide information about the state of the prosthesis and what it is touching. Auditory sensory substitution can be achieved, for example by having the force of a grasp modulating the pitch, timbre or volume of auditory signals. Lundborg *et al.* [39] and, more recently, Gonzales *et al.* [40] demonstrated that by conveying the information relative to the movement of different fingers by different sounds, it is possible to employ auditory feedback to convey artificial proprioceptive and exteroceptive information. Wheeler *et al.* developed a new sensory substitution device that stretches the skin in order to convey the position and motion of prosthetic joints [41].

### Modality-matched feedback

Feedback is said to be modality matched when the output stimulus is felt in the same modality as the sensory input (FIGURE 2), for example, touch on the prosthesis felt as a touch. Reproducing pure modality-matched feedback has been a continuing challenge for researchers in this field, since the training to associate output stimuli to sensory



inputs would be virtually effortless to the amputee, and the stimuli would be felt as natural. Unfortunately, this represents a nontrivial task, and modality-matched feedback is practically difficult to achieve. In his interesting work, Riso [42] reviewed the potential strategies to provide modality-matched feedback to amputees.

In theory, it is possible to regain modality-matched touch sensations (contact, normal and shear force/pressure, vibration, texture, temperature) using noninvasive electromechanical devices coupled with thermoelectric devices (e.g., Peltier cells) [43] applied onto the skin, for example of the residual limb [23,44], the chest [45,46] and other body parts [47]. Modality-matched proprioception is intrinsically a trickier exercise for engineers, since the joint angle (e.g., of the fingers, or of the wrist) needs to be transferred to another sound joint, in order to match the modality. This concept grounds one of the principles of prosthetic design: extended physiologic proprioception introduced by Simpson [48]. Extended physiologic proprioception means that the human-machine interface is configured such that the body's own physiological mechanisms are directly related to the activation and sensing of the device being controlled. Weir *et al.* [49] conveyed prosthesis state by interfacing the prosthesis directly with cineplastized muscles on residual limb of amputees, whereas Gillespie *et al.* [50] employed an exoskeleton to provide the grip reaction force as a reaction torque about the elbow. The techniques were demonstrated to increase the efficacy of control. A different approach to modality-matched proprioception is that discovered by Goodwin *et al.* [51], lately exploited by Roll and Gilhodes [52], which demonstrated that if a localized vibratory stimulus (in the range of 40–80 Hz) is applied over the tendons at the wrist, normal subjects perceive movement of the wrist joint when in fact there is no motion. To explain these effects, it has been theorized that vibrating the flexor tendons induces neural activity in stretch receptors; hence such findings suggest that if the appropriate spindle afferents were stimulated in an amputee's sensory nerve, then feedback of hand position might be possible.

### Mechanotactile stimulation

Mechanotactile feedback is accomplished when a force normal to the skin is applied by a pusher to convey sensory information. This represents a modality-matched sensory feedback paradigm, when force sensors in the fingers are used to detect the sensory input (FIGURE 2). The main features of this class of stimulators are accuracy (how accurately the output force/pressure resembles the sensory input), precision, range, resolution and bandwidth (or its inverse concept, i.e., response time). Drawbacks like complex miniaturization, weight and energy consumption hamper the exploitation of current haptic/robotic technologies in portable systems. In addition, since these systems are usually constituted by moving parts with a mechanical inertia, another limit is the response of the system that in many cases is slow.

One of the most clever examples of mechanotactile feedback in prosthetics is the concept proposed by Rosset (1916) in which a pneumatic system composed of pressure pads and a tube transmitting pressure from the fingers of the prosthesis to the residual limb, directly [6]. This concept was further investigated and implemented using the phantom hand map as the target

for sensory feedback by Antfolk *et al.* [44]. Other examples are the works by Meek *et al.* [53], which embedded force sensors in a cable driven Dorrance hook to provide force feedback using a single motor-driven pusher on the skin of the forearm, and by Patterson *et al.* [54] that employed a pneumatic cuff to display single-site pressure feedback on the arm. Antfolk and colleagues proposed the concept of a multisite mechanotactile system and exploited it to investigate localization and pressure level discrimination on the residual limbs of transradial amputees [55]. Panarese *et al.* targeted a different body area: they investigated the effects of modality-matched force feedback on the glabrous skin of the big and second toe, demonstrating that individuals were able to integrate it in their control [47]. A state of the art device (and reading) is the work by Kim and colleagues; they developed a display able to regain modality-matched contact, pressure, vibration shear force and temperature sensations [56]. Sensinger *et al.* [45] and Marasco *et al.* [46] investigated the perception threshold and sense of embodiment by employing such a device on the chest of amputees having undergone targeted reinnervation surgery, a method by which skin near or over the targeted muscle is reinnervated with afferent fibers of the remaining hand nerves, hence, when this skin is touched, it provides the amputee with a sense of the missing arm or hand being touched.

### Direct neural stimulation

Since action potentials travel in the form of electrical signals, in pure theory it could be possible to recover all somatic sensory information (i.e., touch, proprioception and temperature) with modality matching, using invasive neural electrodes implanted in the peripheral nervous system, in afferents originally serving the fingers and palm (radial, median, ulnar nerve; a complete review on neural interfaces is the work by Micera and colleagues [8]). Experimental evidence demonstrated that this goal is still far from being achieved due to technological limitations of neural interfaces and consequently the still relatively poor knowledge on how the hand encodes stimuli and conveys them to the brain. Direct nerve stimulation showed to be a viable means for eliciting proprioceptive and touch sensations in several studies. Different types of electrodes were employed to convey the information recorded from the prosthesis: cuff electrodes, where electrode wires are wrapped around the nerve [57]; longitudinal intrafascicular electrodes, where electrodes are placed in the nerves longitudinally [9,10,58]; but the quality of the sensation perceived by individuals was frequently a foreign feeling resembling, for example, paresthesia, vibration, tapping or flutter on the skin. These unnatural feelings are thought to be due to the low selectivity of available neural interfaces (that contact bundles of afferents all together), which causes many different types of cutaneous afferents to be activated all at once rather than with precise timing conditions [4]. Techniques to elicit referred tactile or proprioceptive sensations through direct nerve stimulation are similar to those used in noninvasive electrotactile stimulation, although the electrical charge threshold to elicit sensations is one to two orders of magnitude lower (in the order of 0.1–10 nC [10]).

**Table 1. Summary of studies involving sensory feedback in upper limb prosthetics.**

Study (year)	Input	Output	Stimulation position	Main findings	Ref.
Mann <i>et al.</i> (1970)	Elbow joint position	V	Residual limb of upper limb amputee	Improvement of precision and accuracy in positioning tasks with sensory feedback	[22]
Pylatiuk <i>et al.</i> (2006)	Grasp force	V	Residual limb of transradial amputee	A significant reduction of the applied grasping force with feedback	[29]
Cipriani <i>et al.</i> (2008)	Grasp force	V	Upper arm of healthy subjects	Subjective reports stated the feedback system would be useful during grasping task. However, no statistical difference was found between using the system or not	[27]
Chatterjee <i>et al.</i> (2008)	Grasp force	V	Upper arm of healthy subjects	Visual feedback improved performance at all force levels. Training is needed to fully utilize vibrotactile feedback	[26]
Saunders <i>et al.</i> (2011)	Grasp force	V	Forearm of healthy subjects	With feedforward controller uncertainty, after training, either visual or vibrotactile feedback enabled successful task performance	[24]
Scott <i>et al.</i> (1980)	Grasp force	E	Residual limb of transradial amputees	Subjects reported satisfaction with the electrotactile feedback	[34]
Wang <i>et al.</i> (1995)	Grasp force	E	Forearm of healthy subjects	Users can differentiate the appropriate gripping force for a wide class of activities	[36]
Lundborg <i>et al.</i> (1998)	Finger force	E	Upper arm of nerve injury patients and amputees	With feedback, users were able to discriminate location and regulate grip force to predefined levels	[35]
Meek <i>et al.</i> (1989)	Grasp force	M	Forearm of healthy subjects	Successful manipulations of the test's object increased with the use of sensory feedback	[53]
Panarese <i>et al.</i> (2009)	Grasp force	M	The first and second toe of healthy subjects	Participants incorporated sensory feedback received on the foot in their sensorimotor control of a robotic hand	[47]
Sensinger <i>et al.</i> (2009)	Force	M	Reinnervated chest area of amputees	Feedback area had near-normal force sensitivity compared to contralateral normal skin	[45]
Antfolk <i>et al.</i> (2012)	Passive hand touch	M	Residual limb of transradial amputees	Subjects are able to discriminate feedback sites and pressure levels using a completely passive system	[44]
Weir <i>et al.</i> (2001)	Grasp force and finger position	O (EPP feedback)	Residual limb of amputees with cineplasty	Cineplasty and harness-based, body-powered control showed similar performance with lower variability using cineplasty, suggesting a higher consistency	[49]
Wheeler <i>et al.</i> (2010)	Elbow joint position	O (skin stretch)	Upper arm of healthy subjects	Targeting errors in blind movements with the feedback device were lower with feedback.	[41]
Gonzales <i>et al.</i> (2012)	Hand configuration	O (auditory)	–	The usage of an auditory display to monitor and control a robot hand improves the temporal performance greatly, and reduces mental effort.	[40]
Clippinger <i>et al.</i> (1974)	Grasp force	N	Medial nerve of amputees	The patient correlated the grasp force to the sensation provided by direct nerve stimulation	[57]
Dhillon <i>et al.</i> (2005)	Elbow joint position and finger force	N	Median nerve of amputees	Participants could discriminate force applied to the thumb sensor and static position of the elbow joint of the artificial arm	[9]
Rossini <i>et al.</i> (2010)	Finger movement	N	Medial and ulnar nerve of amputees	Phantom limb syndrome was alleviated after 4 weeks of use	[10]

E: Electrotactile; EPP: Extended physiologic proprioception; M: Mechanotactile; N: Direct nervous stimulation; O: Other; V: Vibrotactile.

**Table 1. Summary of studies involving sensory feedback in upper limb prosthetics (cont.).**

Study (year)	Input	Output	Stimulation position	Main findings	Ref.
Horch <i>et al.</i> (2011)	Finger force and position	N	Ulnar and median nerve of amputees	Tactile and proprioceptive feedback is needed when discriminating object size and stiffness	[58]
Patterson <i>et al.</i> (1992)	Grasp force	V, M	Upper arm of healthy subjects	Vision together with mechanotactile feedback produced the lowest error rates	[54]
Marasco <i>et al.</i> (2011)	Passive hand touch	V, M	Reinnervated area of the upper arm of amputees	Physiologically appropriate sensory feedback appears to elicit an incorporation of a prosthetic limb into the self-image	[46]
Antfolk <i>et al.</i> (2012)	Passive hand touch	V, M	Forearm of healthy subjects and residual limb of forearm amputees	Placement of feedback devices on a complete phantom map improves multisite sensory feedback discrimination	[55]

E: Electrotactile; EPP: Extended physiologic proprioception; M: Mechanotactile; N: Direct nervous stimulation; O: Other; V: Vibrotactile.

### Expert commentary

Research in the field mainly focuses on sensory substitution in battery-powered prostheses, and can be roughly classified in three different kinds of studies: works where new devices or stimulation techniques were investigated in psychophysics studies (e.g., [10,17,55]), works in which sensory feedback systems were used in matching force or position paradigms [26,29,41] and research that focused on applied scenarios studying if feedback aided performance in functional grasping tasks [24,27,50]. TABLE 1 summarizes some of these studies. Results from psychophysics studies corroborated the idea of providing sensory feedback through pathway B; as an example, the number of just-noticeable differences was estimated at between 6 and 59 levels for electrotactile stimulation and 15 levels for vibrotactile [16]. Moreover, matching force/position studies generally demonstrated improved control accuracy when extended feedback is added to vision alone. Finally, outcomes from studies that investigated functional grasps using actual prostheses and sensory substitution have been positive (i.e., subjects considered the feedback important and/or the performance slightly improved), but however, not of the expected significance. It appeared that when visual feedback could be used, the additional (modality mismatched) sensory feedback was not practically exploited. We argue that known sensory substitution techniques can be perceived only at the conscious level, and they require a cognitive load far beyond the one needed for processing visual input, due to the modality mismatch that the CNS has to interpret. To overcome this limitation, we suggest to present sensory substitution feedback in more physiological ways: one possibility is to stimulate afferent pathways that served the limb, as in the works by Marasco *et al.*, where feedback was delivered on the chest of targeted reinnervated amputees [46] or by Antfolk *et al.*, which exploited referred phantom finger maps on the residual limb [23,44]. In both cases, the stimulation was felt as if it was coming from the phantom fingers, or in other words somatotopically matched. Under such hypotheses, we expect that physiologically relevant feedback would aid the control of functional grasps alongside modality mismatch stimulation. An alternative way to bring artificial feedback to the unconscious level is to

get inspiration from human sensory motor mechanisms and try to substitute them, as proposed by the discrete sensory-event driven control technique described by Johansson and Edin [13]. Direct neural stimulation and mechanotactile displays can also represent viable ways to present functionally-usable feedback, but from our point of view, they still have to overcome challenging clinical and technological limitations before becoming of practical use. Ironically, after decades of research in upper limb prosthetics, robotics, haptics and applied neuroscience, it is the very simple architecture of the body-powered prosthesis dating back to 1912, that remains the only device coming close to providing physiologically correct and acceptable sensory feedback to the user.

### Five-year view

Advanced robotic hands or multifingered prostheses are nowadays available to a wide audience of researchers. Therefore, it is expected that studies using physical devices and focusing on the contribution of sensory feedback to the performance of functional activities will be carried out more frequently. These studies should focus on the identification of which information, collected by the sensors embedded in the prostheses, are important for the control of the prosthesis by choosing the information to deliver to the user and comparing the task performance. New research on direct neural stimulation of the peripheral nervous system using more selective neural interfaces should be carried out in humans in order to provide important perspectives on its clinical viability, as well as improve knowledge of hand-brain communication, which is particularly important for the realization of devices capable of providing modality-matched sensations.

Currently, available vibrotactile motors are very small, cheap and low-power. They have already entered the prosthetic-components market (in 2002 the Boston elbow was featured with a vibrotactile unit to acknowledge the user of the state of the prosthesis) [204], and it is expected that vibrotactile units will become available with multifingered hands equipped with motor-torque sensors, hence providing contact and/or force feedback. In this way, the effect of feedback devices in daily use in the control of prosthesis could be evaluated on amputees.

### Financial & competing interests disclosure

The work of the authors is supported by the Italian Ministry of Education University and Research under the FIRB-2010 MY-HAND Project [RBF10VCLD], by the European Commission under the WAY project (FP7-ICT-228844), by the Swedish Research Council, the Crafoord foundation, the Promobilia foundation, and by the Skåne County Council

Research and Development foundation. The authors have no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed.

No writing assistance was utilized in the production of this manuscript.

### Key issues

- Since natural grasping largely relies on tactile feedback, a common thought is that prostheses would function better if they used closed-loop control, making use of both exteroceptive as well as proprioceptive information.
- None of today's prostheses have purposely designed sensory feedback. Body-powered prostheses provide awareness of the terminal device through the control cable. Battery-powered prostheses provide only incidental clues. Hence, users largely rely on vision.
- Sensory feedback can be elicited invasively, by interfacing directly the nerves or noninvasively, by providing feedback on the skin. Training by the individual is always required.
- Sensory substitution was often investigated in prosthetic research. Prevalent techniques have been vibrotactile and electrotactile. Although the sensation is substituted, these devices are of low cost and low power, and can actually be integrated in the prosthetic socket.
- Modality-matched feedback is achievable with noninvasive mechanotactile devices; however, these are bulky, power consuming and expensive.
- Direct nerve stimulation is a viable means for eliciting proprioceptive and touch sensations, but the quality of the sensation is usually a foreign feeling, due to technological limitations of today's neural interfaces.
- Timing of feedback is important. Delay from the sensory input should be in the order of milliseconds. Discrete sensory feedback (i.e., noncontinuous) could be a viable technique for making feedback effective and avoiding adaptation.

### References

Papers of special note have been highlighted as:

- of interest
- of considerable interest

- Biddiss E, Beaton D, Chau T. Consumer design priorities for upper limb prosthetics. *Disabil. Rehabil. Assist. Technol.* 2(6), 346–357 (2007).
- Kyberd PJ, Wartenberg C, Sandsjö L *et al.* Survey of upper-extremity prosthesis users in Sweden and the United Kingdom. *J. Prosthet. Orthot.* 19(2), 55–62 (2007).
- Weir R, Sensinger J. The design of artificial arms and hands for prosthetic applications. In: *Biomedical Engineering and Design Handbook (Volume II: Applications)*. Kutz M (Ed.) McGraw-Hill, NY, USA, 537–598 (2009).
- Johansson RS, Flanagan JR. Coding and use of tactile signals from the fingertips in object manipulation tasks. *Nat. Rev. Neurosci.* 10(5), 345–359 (2009).
- Scott RN. Feedback in myoelectric prostheses. *Clin. Orthop. Relat. Res.* 256, 58–63 (1990).
- Childress DS. Closed-loop control in prosthetic systems: historical perspective. *Ann. Biomed. Eng.* 8(4–6), 293–303 (1980).
- Historical review on feedback in prosthetics.
- Chappell PH. Making sense of artificial hands. *J. Med. Eng. Technol.* 35(1), 1–18 (2011).
- Micera S, Carpaneto J, Raspopovic S. Control of hand prostheses using peripheral information. *IEEE Rev. Biomed. Eng.* 3, 48–68 (2010).
- Dhillon GS, Horch KW. Direct neural sensory feedback and control of a prosthetic arm. *IEEE Trans. Neural Syst. Rehabil. Eng.* 13(4), 468–472 (2005).
- Rossini PM, Micera S, Benvenuto A *et al.* Double nerve intraneural interface implant on a human amputee for robotic hand control. *Clin. Neurophysiol.* 121(5), 777–783 (2010).
- Borvinick M, Cohen J. Rubber hands 'feel' touch that eyes see. *Nature* 391(6669), 756 (1998).
- Shimada S, Fukuda K, Hiraki K. Rubber hand illusion under delayed visual feedback. *PLoS one* 4(7), e6185 (2009).
- Johansson RS, Edin BB. Predictive feed-forward sensory control during grasping and manipulation in man. *Biomed. Res.* 14(4), 95–106 (1993).
- Proposes the use of discrete events feedback for prosthetic control.
- Childress DS. Powered limb prostheses: their clinical significance. *IEEE Trans. Biomed. Eng.* BE20(3), 200–207 (1973).
- Johansson RS, Westling G. Signals in tactile afferents from the fingers eliciting adaptive motor responses during precision grip. *Exp. Brain Res.* 66(1), 141–154 (1987).
- Kaczmarek KA, Webster JG, Bach-y-Rita P, Tompkins WJ. Electrotactile and vibrotactile displays for sensory substitution systems. *IEEE Trans. Biomed. Eng.* 38(1), 1–16 (1991).
- Comprehensive work on vibrotactile and electrotactile stimulation.
- Cipriani C, D'Alonzo M, Carrozza MC. A miniature vibrotactile sensory substitution device for multifingered hand prosthetics. *IEEE Trans. Biomed. Eng.* 59(2), 400–408 (2012).
- Jones LA, Sarter NB. Tactile displays: guidance for their design and application. *Hum. Factors* 50(1), 90–111 (2008).
- A comprehensive guide to vibrotactile stimulation.
- Wilska A. On the vibrational sensitivity in different regions of the body surface. *Acta Physiol. Scand.* 31(2–3), 284–289 (1954).
- Shannon GF. A comparison of alternative means of providing sensory feedback on upper limb prostheses. *Med. Biol. Eng.* 14(3), 289–294 (1976).
- Comparison between vibrotactile and electrotactile feedback with aspects of control, acceptability and integration.



- 21 Bach-Y-Rita P, Collins CC. Sensory substitution and limb prosthesis. *Proceedings of the Third International Symposium on Advances in External Control of Human Extremities*. 9–21 (1970).
- 22 Mann RW, Reimers SD. Kinesthetic sensing for the EMG controlled Boston Arm. *IEEE Trans. Man–Mach. Syst.* MM11(1), 110–115 (1970).
- 23 Antfolk C, D'Alonzo M, Controzzi M *et al.* Artificial redirection of sensation from prosthetic fingers to the phantom hand map on transradial amputees: vibrotactile vs. mechanotactile sensory feedback. *IEEE Trans. Neural Syst. Rehabil. Eng.* doi:10.1109/TNSRE.2012.2217989 (2012) (Epub ahead of print).
- 24 Saunders I, Vijayakumar S. The role of feed-forward and feedback processes for closed-loop prosthesis control. *J. Neuroeng. Rehabil.* 8, 60 (2011).
- **Explains the role of feedforward and feedback mechanism in prosthesis control.**
- 25 Sears HH, Iversen E, Archer S, Linder J, Hays K. Grip force feedback in an electric hand – preliminary results. Presented at: *Proceedings of the 2008 MyoElectric Controls/Powered Prosthetics Symposium, MEC'08*. 175–178 (2008).
- 26 Chatterjee A, Chaubey P, Martin J, Thakor N. Testing a prosthetic haptic feedback simulator with an interactive force matching task. *J. Prosthet. Orthot.* 20(2), 27–34 (2008).
- 27 Cipriani C, Zaccane F, Micera S, Carrozza MC. On the shared control of an EMG-controlled prosthetic hand: analysis of user-prosthesis interaction. *IEEE Trans. Robot.* 24(1), 170–184 (2008).
- 28 Pons JL, Ceres R, Rocon E *et al.* Objectives and technological approach to the development of the multifunctional MANUS upper limb prosthesis. *Robotica* 23(3), 301–310 (2005).
- 29 Pylatiuk C, Kargov A, Schulz S. Design and evaluation of a low-cost force feedback system for myoelectric prosthetic hands. *J. Prosthet. Orthot.* 18(2), 57–61 (2006).
- 30 Stepp CE, Matsuoka Y. Relative to direct haptic feedback, remote vibrotactile feedback improves but slows object manipulation. *Conf. Proc. IEEE Eng. Med. Biol. Soc.* 2010, 2089–2092 (2010).
- 31 Szeto AY, Saunders FA. Electrocutaneous stimulation for sensory communication in rehabilitation engineering. *IEEE Trans. Biomed. Eng.* 29(4), 300–308 (1982).
- **Extensive work on electrotactile feedback.**
- 32 Saunders FA. An electrotactile sound detector for the deaf. *IEEE Trans. Audio Electroacoust.* 21(3), 285–287 (1973).
- 33 Sasaki Y, Nakayama Y, Yoshida M. Sensory feedback system using interferential current for EMG prosthetic hand. *Conf. Proc. Joint IEEE Eng. Med. Biol. Soc.* 3, 2402–2403 (2002).
- 34 Scott RN, Brittain RH, Caldwell RR, Cameron AB, Dunfield VA. Sensory-feedback system compatible with myoelectric control. *Med. Biol. Eng. Comput.* 18(1), 65–69 (1980).
- 35 Lundborg G, Rosén B, Lindström K, Lindberg S. Artificial sensibility based on the use of piezoresistive sensors. Preliminary observations. *J. Hand Surg. Br.* 23(5), 620–626 (1998).
- 36 Wang GZ, Zhang XN. Gripping force sensory feedback for a myoelectrically controlled forearm prosthesis. *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, Vols 1–5*. 501–504 (1995).
- 37 Shannon GF. Sensory feedback for artificial limbs. *Med. Prog. Technol.* 6(2), 73–79 (1979).
- 38 Tupper CN, Gerhard GC. Improved prosthesis control via high resolution electro-tactile feedback. *Proceedings of the 1989 Fifteenth Annual Northeast Bioengineering Conference*. 39–40 (1989).
- 39 Lundborg G, Rosén B, Lindberg S. Hearing as substitution for sensation: a new principle for artificial sensibility. *J. Hand Surg. Am.* 24(2), 219–224 (1999).
- 40 Gonzales J, Soma H, Sekine M, Yu W. Psycho-physiological assessment of a prosthetic hand sensory feedback system base on an auditory display: a preliminary study. *J. Neuroeng. Rehabil.* 9, 33 (2012).
- 41 Wheeler J, Bark K, Savall J, Cutkosky M. Investigation of rotational skin stretch for proprioceptive feedback with application to myoelectric systems. *IEEE Trans. Neural Syst. Rehabil. Eng.* 18(1), 58–66 (2010).
- 42 Riso RR. Strategies for providing upper extremity amputees with tactile and hand position feedback – moving closer to the bionic arm. *Technol. Health Care* 7(6), 401–409 (1999).
- **Great work on the potential strategies to provide modality-matched feedback to amputees.**
- 43 Davalli A, Sacchetti R, Fanin S, Avanzolini G, Urbano E. Biofeedback for upper limb myoelectric prostheses. *Technol. Disabil.* 13(3), 161–172 (2000).
- 44 Antfolk C, Björkman A, Frank SO, Sebelius F, Lundborg G, Rosen B. Sensory feedback from a prosthetic hand based on air-mediated pressure from the hand to the forearm skin. *J. Rehabil. Med.* 44(8), 702–707 (2012).
- 45 Sensinger JW, Schultz AE, Kuiken TA. Examination of force discrimination in human upper limb amputees with reinnervated limb sensation following peripheral nerve transfer. *IEEE Trans. Neural Syst. Rehabil. Eng.* 17(5), 438–444 (2009).
- 46 Marasco PD, Kim K, Colgate JE, Peshkin MA, Kuiken TA. Robotic touch shifts perception of embodiment to a prosthesis in targeted reinnervation amputees. *Brain* 134(Pt 3), 747–758 (2011).
- **Shows the capability of embodiment of a prosthesis by using feedback devices.**
- 47 Panarese A, Edin BB, Vecchi F, Carrozza MC, Johansson RS. Humans can integrate force feedback to toes in their sensorimotor control of a robotic hand. *IEEE Trans. Neural Syst. Rehabil. Eng.* 17(6), 560–567 (2009).
- 48 Simpson DC. The control and supply of a multimovement externally powered upper limb prosthesis. *Proceedings of the Fifth International Symposium on Advances in External Control of Human Extremities*. 247–254 (1975).
- 49 Weir RF, Heckathorne CW, Childress DS. Cineplasty as a control input for externally powered prosthetic components. *J. Rehabil. Res. Dev.* 38(4), 357–363 (2001).
- 50 Gillespie B, Baker J, O'Malley M, Shewokis P, Contreras-Vidal JL. Functionally biarticular control for smart prosthetics. *Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. World Haptics 2009. 627–628 (2009).
- 51 Goodwin GM, McCloskey DI, Matthews PB. The contribution of muscle afferents to kinaesthesia shown by vibration induced illusions of movement and by the effects of paralysing joint afferents. *Brain* 95(4), 705–748 (1972).
- 52 Roll JP, Gilhodes JC. Proprioceptive sensory codes mediating movement trajectory perception: human hand vibration-induced drawing illusions. *Can. J. Physiol. Pharmacol.* 73(2), 295–304 (1995).
- 53 Meek SG, Jacobsen SC, Goulding PP. Extended physiologic taction: design and evaluation of a proportional force feedback

- system. *J. Rehabil. Res. Dev.* 26(3), 53–62 (1989).
- 54 Patterson PE, Katz JA. Design and evaluation of a sensory feedback system that provides grasping pressure in a myoelectric hand. *J. Rehabil. Res. Dev.* 29(1), 1–8 (1992).
  - 55 Antfolk C, Cipriani C, Carrozza MC *et al.* Transfer of tactile input from an artificial hand to the forearm: experiments in amputees and able-bodied volunteers. *Disabil. Rehabil. Assist. Technol.* doi:10.3109/17483107.2012.713435 (2012) (Epub ahead of print).
  - 56 Kim K, Colgate JE, Santos-Munne JJ, Makhlin A, Peshkin MA. On the design of Miniature Haptic Devices for upper extremity prosthetics. *IEEE-ASME Trans. Mechatron.* 15(1), 27–39 (2010).
  - 57 Clippinger FW, Avery R, Titus BR. A sensory feedback system for an upper-limb amputation prosthesis. *Bull. Prosthet. Res.* 22, 247–258 (1974).
  - 58 Horch K, Meek S, Taylor TG, Hutchinson DT. Object discrimination with an artificial hand using electrical stimulation of peripheral tactile and proprioceptive pathways with intrafascicular electrodes. *IEEE Trans. Neural Syst. Rehabil. Eng.* 19(5), 483–489 (2011).
- Patent**
- 101 Conzelman JE, Ellis HB, O'Brien CW: US2656545 (1953).
- Websites**
- 201 Otto Bock, SensorHand Speed®. [www.ottobock.com/cps/rde/xchg/ob\\_com\\_en/hs.xsl/6953.html](http://www.ottobock.com/cps/rde/xchg/ob_com_en/hs.xsl/6953.html) (Accessed June 2012)
  - 202 Touchbionics, i-limb ultra. [www.touchbionics.com/products/active-prostheses/i-limb-ultra/](http://www.touchbionics.com/products/active-prostheses/i-limb-ultra/) (Accessed on June 2012)
  - 203 RSL Steeper, BeBionic. [www.bebionic.com/the\\_hand](http://www.bebionic.com/the_hand) (Accessed June 2012)
  - 204 Liberating Technologies Inc., Boston Digital Arm. [www.liberatingtech.com](http://www.liberatingtech.com) (Accessed June 2012)