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Scandinavian Journal of Plastic and Reconstructive Surgery and Hand Surgery
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713691514

Referral of sensation to an advanced humanoid robotic hand prosthesis

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First Published on: 21 September 2009

To cite this Article Rosén, Birgitta, Ehrsson, H. Henrik, Antfolk, Christian, Cipriani, Christian, Sebelius, Fredrik and Lundborg, Göran(2009)'Referral of sensation to an advanced humanoid robotic hand prosthesis',Scandinavian Journal of Plastic and Reconstructive Surgery and Hand Surgery,99999:1,

To link to this Article: DOI: 10.1080/02844310903113107

URL: http://dx.doi.org/10.1080/02844310903113107

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Scand J Plast Reconstr Surg Hand Surg
2009, 1–7, iFirst article

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ORIGINAL ARTICLE

Referral of sensation to an advanced humanoid robotic hand prosthesis

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Abstract

Hand prostheses that are currently available on the market are used by amputees to only a limited extent, partly because of lack of sensory feedback from the artificial hand. We report a pilot study that showed how amputees can experience a robot-like advanced hand prosthesis as part of their own body. We induced a perceptual illusion by which touch applied to the stump of the arm was experienced from the artificial hand. This illusion was elicited by applying synchronous tactile stimulation to the hidden amputation stump and the robotic hand prosthesis in full view. In five people who had had upper limb amputations this stimulation caused referral touch sensation from the stump to the artificial hand, and the prosthesis was experienced more like a real hand. We also showed that this illusion can work when the amputee controls the movements of the artificial hand by recordings of the arm muscle activity with electromyograms. These observations indicate that the previously described "rubber hand illusion" is also valid for an advanced hand prosthesis, even when it has a robotic-like appearance.

Key Words: *Hand prosthesis, artificial hand, sensory feedback, EMG, body ownership, multisensory neurons*

Introduction

Amputation of a hand is a catastrophe that results in considerable disability with enormous consequences for activities of daily living and quality of life. Although functional myoelectric prostheses are available, these are being used to only a limited extent by amputees, partly because of the lack of sensory function. In a normal hand sensory feedback is a prerequisite for regulation of muscle power in the handgrip with fine position manipulation. Sensory feedback also makes the hand a true part of the body; one comes to feel that one owns the limb.

Within the EU-project SmartHand – The Smart Bio-adaptive Hand Prosthesis (www.smarthand.org) one of several aims is to develop sensory functions in an advanced, thought-controlled, hand prosthesis with multiple degrees of freedom. We describe a pilot study that demonstrated how such an advanced hand prosthesis can be perceived as the amputee's own hand, because of the referral of tactile and other somatic sensations from the stump to the prosthesis.

The principle of projecting tactile sensations and the "feeling of body ownership" on to the advanced hand prosthesis was based on the rubber hand illusion that has previously been described for normal people [1–4]. The rubber hand illusion is elicited by synchronously touching the person's hand, placed out of view, and a rubber hand in full view [1–3]. Most participants will start experiencing the sense of touch on the rubber hand, rather than on their real hand, and a feeling that the rubber hand is part of their own body will develop. The illusion is a result of the brain's perceptual systems as they try to interpret the conflicting visual, tactile, and proprioceptive information that lead to a resolution of the conflict by a recalibration of sense of position and the location of touch towards the rubber hand [1]. This process involves multisensory areas of the brain including premotor, parietal, and cerebellar structures [3,5].

We have recently shown that this illusion can be elicited in amputees when synchronous stimulation is applied to the hidden arm-stump and to the

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(Accepted 7 April 2009)

ISSN 0284-4311 print/ISSN 1651-2073 online
DOI: 10.1080/02844310903113107

fingers of a life-like cosmetic prosthesis in full view [6]. To do this it was critical to stimulate the part of the stump that elicited referred sensations in the fingers of the phantom hand. We proposed that this tactile information reached somatosensory hand representations of the missing hand and that these signals were then integrated with the visual information in multisensory areas, thereby eliciting the rubber hand illusion in the amputees [6].

The aim of the present study was to find out if the illusion of referred tactile sensations and body ownership could be evoked in upper limb amputees using an advanced humanoid robotic prosthesis that looks different from a real biological hand. We also wanted to see if the illusion of ownership could be maintained as the amputee voluntarily controlled the movements of the artificial hand by recordings of muscular activity in the lower arm with electromyograms (EMG).

Patients and methods

Patients

Five volunteer amputees, four men and one woman, mean age 38 (24–53) years, participated in the experiments. Two were right-hand amputees and three left-hand amputees. Four amputations were traumatic (time since amputation 2–25 years) while one amputation was congenital. All five were full-day prosthesis users (one aesthetic and four myoelectric). In all amputees there was a "mapped" referred sensation of the missing hand distally on the amputation stump [7,8]. To find out the location of the zones of referred sensations the patient was asked to touch on the stump, and define the referred phantom parts of the hand (digits I–V). The points on the stump were then marked with a pen and after that the patient verified the mapping by touching the marks. If a mapping of digit II was present, it was used during the experiment for simultaneous touching of the stump and the prosthesis; if not digit I was used. Tactile stimulation of individual "fingers" in this map using a little brush induced a feeling of touching the corresponding fingers in the phantom hand. The phenomenon is a result of functional reorganisation, which occurs in the sensory brain cortex after amputation of a hand [9,10].

The artificial hand

The humanoid robotic hand prosthesis named "the Pisa-hand" was developed and provided by the ARTS Lab, Scuola Superiore Sant'Anna, Pisa, and was developed as a part of the EU-project SmartHand – The Smart Bio-adaptive Hand Prosthesis (Sixth framework programme, priority NMP4-CT-2006-00334231) (Figure 1).

It consists of a stand-alone version of the CyberHand developed earlier in the framework of the homonymous EU-project (IST-2001-35094). The hand has five independent fingers powered by six DC motors that allow several degrees of freedom (flexion of individual fingers and opposition of the thumb). The fingers of the prosthesis have been designed accurately to replicate both the appearance (shape and size) and the dynamics of the natural hand as reported by Carrozza et al. [11]. The movements of the prosthesis can be controlled by an external personal computer or by EMG-signals from eight pairs of electrodes positioned on the amputation stump with a delay of about 50 ms in the EMG-controlled system as previously described by Sebelius et al. [12]. The mechanics of this early stand-alone version of the CyberHand was limited with full range closure of the movements of roughly 2 seconds.

Experimental design

The subject was placed in front of a table and the artificial hand (only a right-hand prototype prosthesis is available) was placed in an anatomically correct position on a table 10–20 cm medial and parallel to the hidden amputation stump (Figure 2). From the perspective of the participant the robotic hand looked like a part of their own limb. Because we had only a right-hand robotic prosthesis we had to use a mirror to create a reflection of the artificial hand on the left side for the three left-hand amputees. A mirror was therefore placed obliquely in front of the subject so that the right-hand prosthesis was reflected and visually superimposed as close as possible to the stump, as in the mirror illusion described previously for amputees [13].

The subjects were instructed to relax and observe the robotic hand on the table at the same time as one finger of the artificial hand, and the site that elicited referred sensations in the same phantom finger on the stump (digit I in subject 1 and digit II in subjects 2–5), was brushed synchronously with two soft paint-brushes. The tactile stimulation was continued for two minutes using an irregular rhythm, as this produces the strongest "rubber hand" illusion. The mean frequency of the brushstrokes was 1 Hz and each stroke about 2–3 cm long. The left-hand amputees were instructed to observe the mirror reflection of the artificial hand, which was superimposed over their missing hand, the amputation stump being hidden behind the mirror. Directly after the experiment the patient filled in a questionnaire of nine questions, modified from those used by

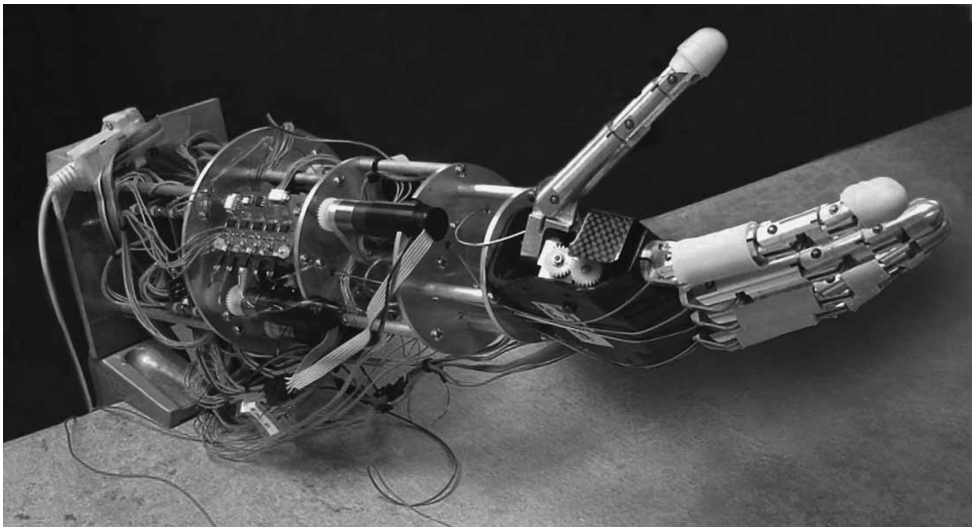

Figure 1. The humanoid robotic hand prosthesis – an early version of "the CyberHand" - developed and provided by the ARTS Lab, Scuola Superiore Sant'Anna developed in the framework of the homonymous EU project (IST-2001-35094). The hand has five independent fingers powered by six DC motors, which allow several degrees of freedom (flexion of individual fingers and opposition of the thumb). The fingers of the prosthesis have been accurately designed to replicate both the appearance and the dynamics of a natural hand [11].

Botvinick and Cohen [1], which required a rating of the strength of agreement or disagreement with nine perceptual statements about possible experiences during the experiments. Three of the questions related to the extent of sensory transfer into the hand and the feeling that the hand was part of their body ("I felt the touch of the brush on the prosthesis", "It seemed that the brush on the prosthesis generated the touch I felt", "I felt as the prosthesis was my hand"), and the other six served as controls for compliance, suggestibility, and "placebo effect" ("I experienced that the stump moved towards the prosthesis", "I felt I had three arms", "It seemed the touching was localised somewhere between the stump and the prosthesis", "The stump started to feel rubbery", "I saw the prosthesis move towards the stump", "The prosthesis started to change shape, colour and appearance, and started to look like my stump"). The participants were asked to rate the extent to which these statements did or did not apply, using a seven-point visual analogue scale. On this scale, -3 meant 'absolutely certain that it did not apply', 0 meant 'uncertain whether or it applied or not', and $+3$ meant 'absolutely certain that it applied.' We compared the mean score on the illusion statements with the mean score from the control statements using a non-parametric test (Wilcoxon two-tailed signed rank test).

To obtain behavioural evidence that the illusion caused a shift in the perceived location of the touches felt towards the prosthesis, a "pointing task" was required (adopted from Ehrsson et al. [6]). We exposed the participants to the stump-illusion condition and a control condition for periods of 60 seconds, presented three times each. The control stimulation comprised asynchronous touches applied to the rubber hand and the stump. It is well established that asynchronous stimulation strongly reduces the rubber hand illusion in normal participants [2–4]. Immediately before (after five brushstrokes were delivered to the stump) and after the stimulation trials, the participants were required to close their eyes and point to where they had felt the touch. A ruler mounted on the table was used to measure the end point of each movement. The pointing drift was calculated as the distance between the indicating index finger and the stump after the stimulation period minus the distance between the indicating index finger and the stump before the stimulation period. We then compared the "tactile drift" between the synchronous and asynchronous conditions. We did not analyse the data statistically because the pointing task is highly variable and requires larger groups of participants.

In two of the patients who had good motor control of the prosthesis after roughly two hours training with the multiple EMG-induced control system (cases 2 and 5) we wanted to see if the illusion could be produced when the amputees controlled the movements of the artificial hand myoelectrically. Both of them were also every-day users of myoelectric prostheses. Case 2 had had the right hand amputated, and case 5 had had the left hand amputated, meaning that case 5 used the mirror during the experiments. In these experiments the amputee controlled the movement of the artificial hand with EMG signals derived from multiple surface electrodes on the amputation stump [12]. The

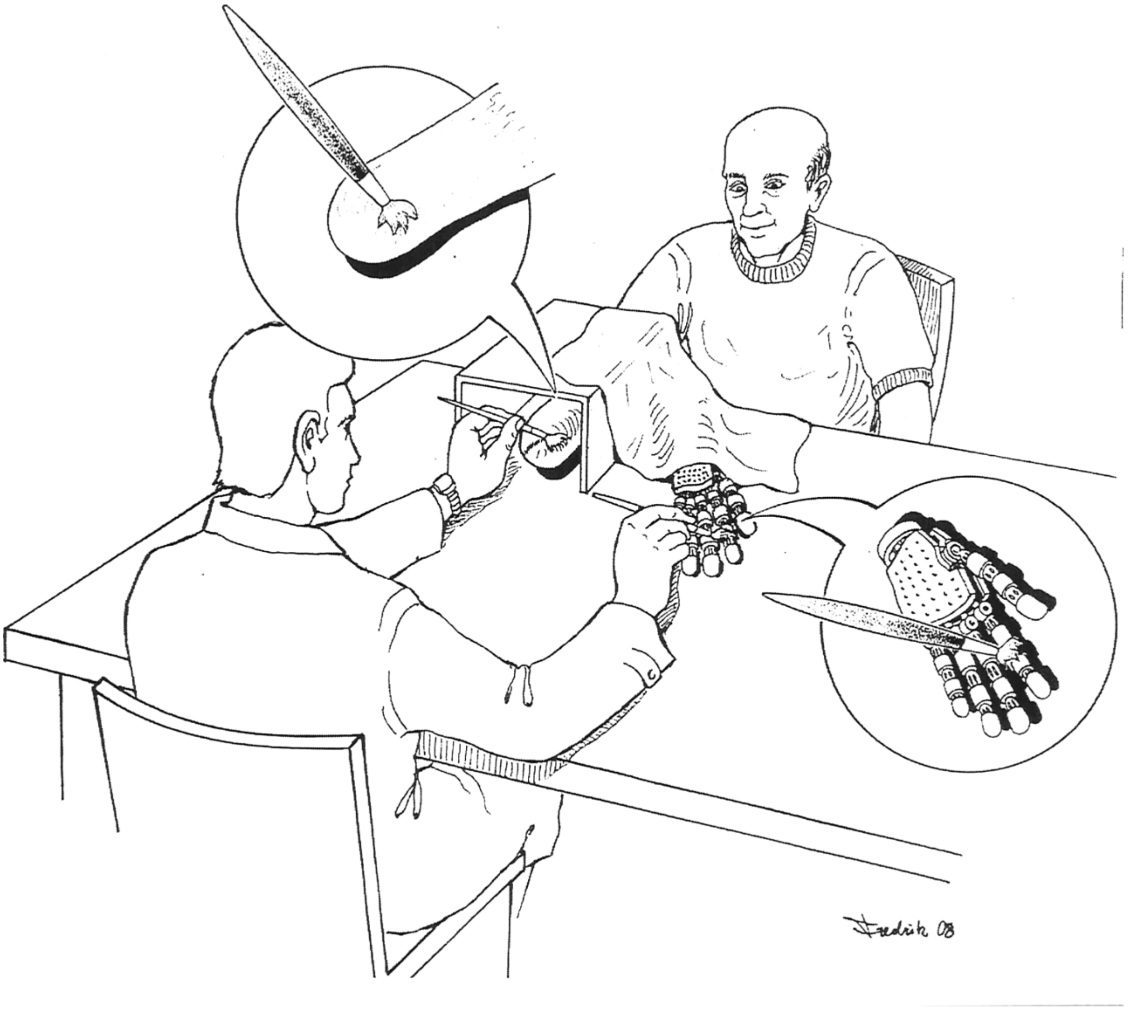

Figure 2. Experimental design for sensory transfer into a robotic hand for an upper limb amputee. The subject was placed in front of a table and the artificial hand was placed in an anatomically plausible position on the table 10–20 cm medially and parallel to the hidden amputation stump. Simultaneous and synchronous brushing were applied to the hidden amputation stump with the robotic hand in full view.

artificial hand was connected by wires to electrodes on the hidden amputation stump for multiple EMG-induced movements. The experiment was done after only two hours' training with the multiple EMG-induced control system. This specific artificial hand has five independent fingers powered by six DC motors that allow several degrees of freedom (flexion of individual fingers and opposition of the thumb). The participants trained to generate seven different movements (opposition of the thumb, flexion of the thumb, flexion of the index finger, flexion of the long finger, flexion of all four fingers, pinch grip, key grip, and making a full fist). During this part of the experiment the subjects were free to move in the patterns in which they felt most comfortable.

In the actual experiments the prosthesis was positioned as in the previous experiment, with the prosthesis in an anatomically acceptable position and the hidden amputation stump provided with 8 pairs of EMG electrodes. The subjects were instructed to observe the movements of the robotic hand prosthesis that they generated voluntarily. We tested two conditions; first when the amputees simply "moved" the artificial hand and looked at it without any added tactile stimulation; and secondly the myoelectrically-controlled movements in combination with simultaneous brushing of the stump and robotic hand. We predicted that the latter condition would to produce the strongest illusion.

After three minutes a statement was presented ("I felt as the prosthesis was my hand"). The participants were asked to rate the extent to which this statement did or did not apply, using the seven-point visual analogue scale as described earlier. Spontaneous remarks made by the participants were noted, as when they responded to open-ended questions about their experiences.

Results

In the first experiment all five subjects reported somatosensory sensations from the artificial hand ("sensory transfer") (scores of +1 or higher) in a minimum of one of the three critical statements. Three of the subjects had a strong illusion (+2 or 3). The subjects consistently rejected the control statements. The difference between the scores on the illusion and control statements was significant ($p = 0.043$, 2-tailed, $N = 5$, $Z = -2{,}023$, Wilcoxon signed rank test). The illusion therefore seemed to work with a humanoid robotic hand in amputees. The phenomenon occurred regularly within the first minute of stimulation as inferred from the participant's spontaneous remarks.

In the pointing task there was a greater drift in three of the cases in the perceived location of the touches towards the robotic hand after the synchronous stimulation than after the asynchronous stimulation. This was the case in one of the participants with the right hand amputated and two of the three who used the mirror during the experiment. This provides objective behavioural evidence for the illusion.

Two of the participants (cases 2 and 5) with voluntary EMG-control of the artificial hand movements, also gave evidence a transfer of somatic sensations and ownership on to the prosthesis, +1). Importantly, the rating scores of one of the participants were substantially higher when the EMG-controlled movements were supplemented by the synchronous brushing of the amputation stump and the artificial hand (+3). Both participants also made convincing remarks during the experiments suggesting that they had experienced the illusion. "*... when you touched the thumb simultaneously as the phantom thumb on my stump for a moment I forgot that you touched the stump - it became a real sensibility – but I know it is a prosthesis*", "*It feels like my hand, but it feels like a very cold hand – a bit numb*".

Discussion

Our results suggest that the rubber hand illusion can be induced in amputees using an advanced humanoid robotic hand prosthesis. Three of the five subjects reported a strong illusion and the other two a moderate illusion. Our results also indicate that the illusion of ownership can be induced when the amputees control the movements of the artificial hand using EMG signals from the stump. These observations are interesting, because they suggest that a patient with a normal mind can be tricked into experiencing an advanced humanoid robotic hand prosthesis as part of their own body. This could have important clinical applications for the development of the next generation of artificial limbs.

There are a number of reasons why the present effect could be produced by the same mechanisms that generate the rubber hand illusion in normal participants. First, the timing of the effect is similar. In the amputees the illusion is weaker than in uninjured people but it occurs within minutes. The illusion disappeared if the brushings of the robotic hand prosthesis and the real hand were made asynchronously, or if the artificial hand was placed in an anatomically implausible position. Again, in normal participants such manipulations also break the illusion [3]. Finally, although we had data from only five participants, three of them had an objectively measurable drift in the perceived location of the touches towards the artificial hand, similar to the proprioceptive drift described for the traditional rubber hand illusion [1,4].

We have recently reported that the rubber hand illusion can be induced in upper limb amputees using a life-like cosmetic hand prosthesis. In these experiments the amputation stump was hidden behind a screen and brushed simultaneously with brushing of a hand prosthesis in full view and with the appearance of a normal hand [6]. The effect was most obvious when an individual finger, the index finger, of the prosthesis was brushed simultaneously with the "index finger" in the mapping of the phantom hand, which very often occurs distally in the amputation stump. Such a hand map is a result of reorganisation changes, which occur in the somatosensory brain cortex after hand amputation [9]. The present data provides two clinically important extensions of this earlier work. First it shows that the illusion can also be made to work with an advanced robotic artificial hand that does not look like a biological hand at all. Previous reported experiments were all performed on rubber hands looking like normal hands. In our experiments we instead used an advanced hand prosthesis prototype of robotic metallic appearance with electronic cables and wires visibly. Secondly, the present results suggest that the illusion can be maintained as the participants voluntarily "moves" the artificial hand with myoelectric control.

In three cases of amputation of the left hand, the right-hand prosthesis was reflected in a mirror so that the amputees experienced a superimposed mirror image over the missing left hand that was being touched. Interestingly the visual observation was strong enough to induce the phenomenon, even based on a mirror reflection. Two of the left-hand amputees using the mirror during the experiment reported the strongest illusion of body ownership for the robotic hand prosthesis (+3 in all three questions). The mirror reflection of the prosthesis was visually superimposed on the missing left hand. Thus there was less spatial discrepancy between the position of the seen robotic hand and the stump, which is likely to enhance the illusion. In normal people the smaller the distance between the stimulated limb and the rubber hand, the stronger the illusion [14]. The largest pointing error in the pointing test (the greatest drift in the perceived location of the touches towards the robotic hand after the synchronous stimulation) was seen in two of the patients who used the mirror during the experiment. In future experiments in which the artificial hand is attached directly on to the stump this might produce an even stronger illusion than at present, where the robotic hand was medially displaced 10–20 cm from the stump.

An interesting unexpected observation was that the two amputees that controlled the movements of the artificial hand by their own EMG signals reported a moderate illusion even when no brushing was applied. When the brushing was added it produced a strong illusion in one of the two participants, which was consistent with our hypothesis that it should be possible to maintain the rubber hand illusion even during myoelectric control. Does this mean that the rubber hand illusion could be elicited even without simultaneous visual and tactile stimulation? Our data in two participants will not settle this issue and there are several alternative explanations that first need to be considered.

During the myoelectric control of the artificial hand movements there is a match between the amputee's motoric intentions and the visual feedback from the artificial hand. Such a match between intended movements and sensory feedback is known to produce a sense of agency, an experience that the person is the author of the action [15,16]. This sense of agency is probably not the same thing as the feeling of ownership [17] because a patient can readily experience agency of external objects, without any changes in ownership. It is likely, however, that the amputees developed a strong sense of agency during the myoelectric control of the artificial hand and that this could have biased the participants when asked to rate statements about ownership in the questionnaires. Another reason for caution is that we had no control of the myoelectric condition, so we cannot be sure that it was the match between intentions and feedback (agency) that caused the ratings to go over 0 or if it was just the fact that the person was looking at a human-like hand. However, what is clinically relevant here is that the illusion induced by brushing the prosthesis and stump does not necessarily break down as the participant controls its movements myoelectrically.

Induction of sensory transfer into an advanced hand prosthesis, as described here, is an important phenomenon, which may form a base for training protocols that focus on systems for sensory functions in future hand prostheses. The sensory transfer is maintained only as long as the stimulated hand is observed, but it disappears as soon as the observation of the prosthesis is interrupted. For clinical applications it would obviously be important to have a robust sense of ownership of the prosthesis even when the person is not directly looking at it, and during periods without tactile stimulation. We know of no long-term studies that have investigated whether there is a learning effect over time when the rubber hand illusion is repeated and continued for hours or repeated for many days. However, technical solutions for the delivery of sensory feedback in hand prostheses are under development [18–21], including arrays of stimulators that could be placed on the stump and attached to sensors in the fingers of the artificial hand.

In principle it would be possible to maintain the illusion of the rubber hand as described here in everyday use. Indeed, we know that illusion of the hand ownership can be maintained during natural activities such as a handshake with another person [22]. Every time a specific part of the prosthesis touches an object it would immediately cause a tactile stimulation on the stump, tricking the multisensory brain into feeling touch from the artificial finger. Such a method could provide a way to restore basic conscious tactile feedback from the prosthesis [20,23], and may form an experimental base for permanent sensory feedback in hand prostheses. The referral of somatosensory sensations by multisensory illusions as described here may play an important part in the training process necessary to establish useful sensory functions in future hand prostheses.

Acknowledgements

This study was supported by grants from EU-project SmartHand - The Bio-adaptive Hand Prosthesis (Sixth framework programme, priority NMP4-CT-2006-00334231), the Swedish Medical Research Council, project no 5188, the Faculty of Medicine, Lund University, Malmö University Hospital. H.H.E was supported by the European Research Council, the Swedish Foundation for Strategic Research, and the Human Frontier Science Programme.

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