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ELEKTRIČNA STIMULACIJA AFERENTNIH VLAKANA PODLAKTICE POVRŠINSKIM ELEKTRODAMA ZA SENZORNU SUPSTITUCIJU

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Abstract

This study aims to determine the optimal parameters and equipment configuration that would allow for information from the real world, concering grasping objects with an artificial hand, to be more intuitively delivered to the patients, by means of electrical stimulation of cutaneous receptors. The results show that different pulse duration and pulse rate for a fixed current amplitude elicit different intensity and different modality of sensation. The subjects reported perceiving at least 4 and up to 7 different sensation modalities, such as itching, tingling, vibration, etc, when different stimulation parameters were applied. The study tested the ability of subjects to discriminate the origins of stimuli in terms of location and concluded that for optimal results, electrodes should be placed circularly around the forearm and in a zigzag pattern. The final measurements included testing of the ability to associate a stimulus of a recognizable intensity and/or quality on a certain location with a type of grasp. The corresponding grasp was shown in a picture when the stimulus was applied in the training process. The subjects were subsequently asked to recall the associated image when stimuli were delivered in a random order, without looking at the screen. The rate of correctly recalled images was above 80%, suggesting that it would be possible to implement a system that would stimulate a certain spot and cause a specific sensation on it consistently when an object of predefined size range was grasped through a predefined grasp, giving thus the subject a feedback, without having to always look at the object being held. This is expected to make the patients feel more comfortable using a prosthetic hand, and experiencing it more as a part of their own body.

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List of abbreviations

TENS	*Transcutaneous Electrical Nerve Stimulation*
CNS	*Central Nervous System*

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1. INTRODUCTION

The use of electrical stimulation in medicine today is rather widespread, ranging from diagnostic, through therapeutic to cosmetic purposes. However, the knowledge of beneficial effects of electricity for the human body is not of a recent date. The first documented report about this phenomenon was left by Scribonius Largus, year 46 AD.[1], who mentions using electric fish for the treatment of headaches and gout. There are also some indications that this was already known in Ancient Egypt 2500 years BC. [1] In the year 1737, an Italian physician, physicist and philosopher Luigi Aloisio Galvani noticed that the muscles of a dead frog contract once an electrical impulse is applied onto them. This later led to studies of electrical signals of the nervous system.

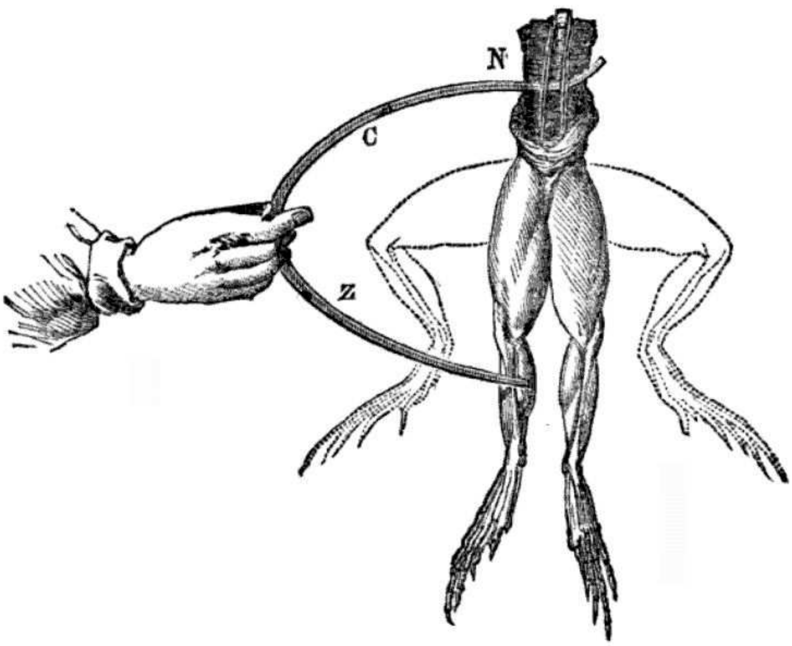

Figure 1. Luigi Galvani discovered that frog's legs twitch when electricity is passed through the muscle. [2]

[1] *Compositiones Medicae*, 46 AD.

The use of electric currents applied transcutaneously to stimulate the nerves is known as *TENS – Transcuaneous nerve stimulation*, and is often thought of in a narrower sense to imply the use of electricity for therapeutic purposes to treat pain. However, this thesis utilizes TENS for eliciting various sensations such as touch, tingling, tickling, etc. on subjects that are not experiencing any pain. Low amplitude electric currents delivered to the skin through surface electrodes excite the cutaneous receptors, resulting in perception of different qualities of sensation depending on the stimulation parameters used. The nature of these receptors will be described in more detail in the following chapters. The experiments described later on seek to determine the optimal configuration of equipment and generated signals that would allow the artificially created tactile sensations in the forearm to act as a substitute for tactile sensations in a hand that has been amputated. The aim is not, however, to simulate the exact feeling that the missing hand would have supplied, but rather to rely on the ability of the human brain to make new associations, thus through extensive practice, learning to identify new sensations on the forearm as a sign of a certain event taking place on an artificial hand.

Development of highly functional hand prosthetics is receiving active endeavor from engineers and scientists of different profiles in the world. With the hand being a very complex body part and a high precision instrument, recreating as many of its functions as possible through prosthesis is one of the greatest challenges for medical technology. A famous example is the Michelangelo hand produced by Otto Bock and Advanced Arm Dynamics, an anthropomorphic hand operated by arm muscle movements translated into electrical signals with the help of electrodes and electromyography software. The hand allows for numerous positions necessary for different kinds of grasps. [3] Its wrist movements are shown in Fig.2. Some other examples can be found in [4 -7]. Nonetheless, there are currently no commercially available artificial hands that provide the user with tactile feedback, and this work is a direct attempt to contribute to this goal, seeing how having feedback helps the patients feel more confident and comfortable using prosthetic limbs. The prototype developed within the SmartHand Project was described by a test subject with the following words: "*I am using muscles which I haven't used for years. I grab something hard, and then I can feel it in the fingertips, which is strange, as I don't have them anymore. It's amazing*" [8]

Figure 2. Otto Bock Michaelangelo hand. [3]

2. RELATED WORK

In 1991 Kaczmarek et al. [9] summarized the technology developed by that time by many investigators for presenting information to the skin by electrical and mechanical stimulation, and gave a solid basis for further research in overcoming limitations in sensory substitution systems. Here we can find information on sizes of cutaneous receptor fields, the range of stimulation parameters and possible elicited sensations, as well as sensation and pain thresholds. A recent study paid close attention to the issue of sensation and pain thresholds with regard to the positioning of electrodes for stimulation on the forearm. [11] The authors found that the thresholds differed significantly for five stimulated locations, that dual-channel stimulation lowered the perception threshold and led to smaller variance in perception thresholds compared to single-channel stimulation, that the perception threshold was inversely related to the number of pulses and that it increased with increasing interleaved time between a pair of electrodes, when the time was below 500μs. The perceptual properties of electrocutaneous stimulation, including subjectively perceived intensity and quality were addressed as early as 1981 in [14].

As the lack of sensation was vastly recognized as the main drawback to using prosthetic limbs, a group of Japanese scientists tested an electric feedback system with higher frequencies (~4kHz) concluding it to be a usable form of stimulation for feedback purposes [15].

Research has also been done in the direction of vibrotactile stimulation for feedback, such as in [16].

The differences in sensation quality with regard to electrostimulation spot were addressed in [17], demonstrating the prevalence of different types of sensations on different locations on the forearm.

3. THEORETICAL BASIS

3.1. Cutaneous receptors

Cutaneous receptors, i.e. the receptors found in the skin, can be classified into mechanoreceptors, thermoreceptors and nociceptors. Nociceptors respond to potentially damaging stimuli by sending nerve signals to the CNS (*central nervous system*) and this process (nociception) usually causes the perception of pain. Thermoreceptors react to absolute and relative changes in temperature. Temperatures likely to damage an organism are sensed by sub-categories of nociceptors that may respond to noxious cold, noxious heat or more than one noxious stimulus modality (polymodal). The largest number of receptor types are mechanoreceptors, and those are:

- Ruffini's end organs
- Meissner's corpuscles
- Pacinian corpuscles
- Merkel's discs
- Mechanoreceiving free nerve endings
- Hair follicle receptors

Ruffini's end organs are slow-adapting (tonic) receptors, sensitive to stretching and inner motion. Placed in the dermis, ligaments and tendons and constitute about 20% of mechanoceptors in the arm.

Meissner's corpuscles are fast-adapting (phasic) receptors with a small receptive field, giving sensations of delicate touch and vibrations at about 50Hz, and allow for spatial discrimination. Mainly localized in fingertips, lips and tongue, and make up about 40% of receptors in the arm.

Pacinian corpuscles are phasic receptors with a large receptive field, activated by touch and vibrations (200-300 Hz). Localized deep in the dermis and constitute about 10-15% of arm mechanoreceptors. Constituted of unmyelinated nerve endings coated with connective tissue.

Merkel's discs are slow adapting receptors with a small receptive field, which makes them sensitive to pointy stimuli. Primarily localized in fingertips and constitute about 25% of arm receptors.

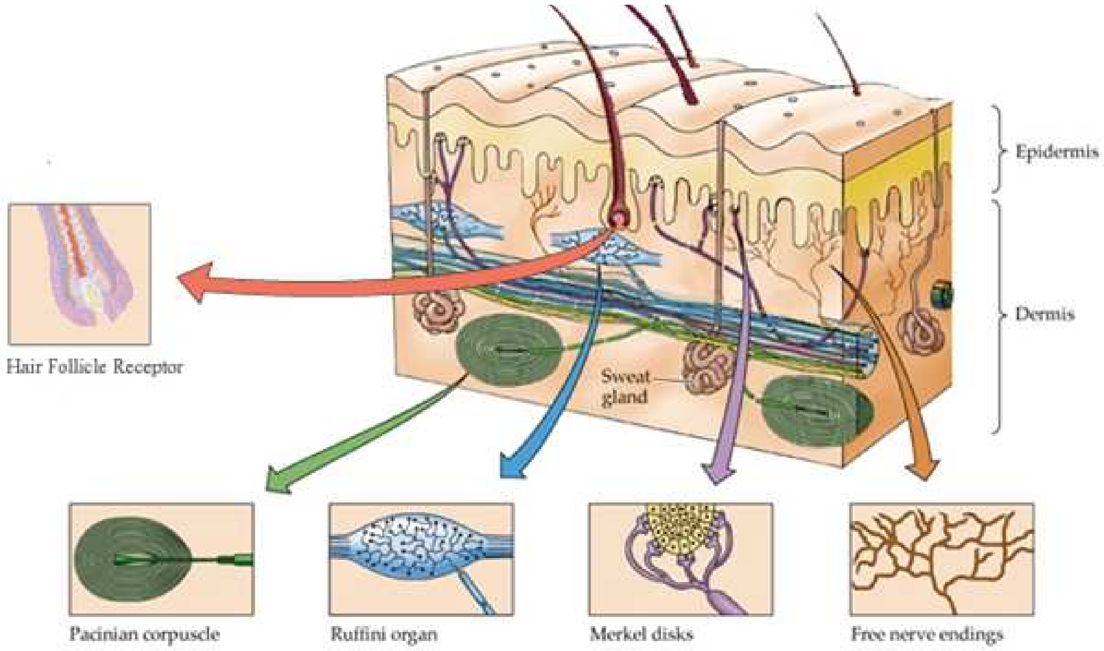

Figure 3 Mechanoreceptors of hairy skin [19]

To clarify, a slowly adapting receptor is a mechanoreceptor that responds slowly to stimulation and continues firing as long as the stimulus continues. On the other hand, a fast adapting receptor responds quickly to stimulation but rapidly accommodates and stops firing if the stimulus remains constant. Fig 3. gives a graphic representation of cutanous receptors, whereas Fig 4. shows data on each type of mechanoreceptors, including the size of the receptive fields, the frequency to which the receptors respond best, and more.

PROBABLE RECEPTOR	CLASS (STEP INDENTATION RESPONSE)	RECEPTIVE FIELD (mm^2) (MEDIAN)	SKIN TYPE *	FREQUENCY RANGE (MOST SENSITIVE)	THRESHOLD SKIN DEFORM ON HAND (MEDIAN)	PROBABLE SENSORY CORRELATE	RECEPTORS/cm^2 FINGERTIP (PALM)
PACINIAN CORPUSCLE	**FA II** (RA II, QA II, PC)	10-1000 (101)	G,H	40-800 Hz (200-300 Hz)	3-20 μm (9.2 μm)	VIBRATION TICKLE	21 (9)
MEISSNER'S CORPUSCLE	**FA I** (RA I, QA I, RA)	1-100 (12.6)	G	10-200 Hz (20-40 Hz)	4-500 μm (13.8 μm)	TOUCH TICKLE MOTION VIBR FLUTTER TAP	140 (25)
HAIR FOLLICLE RECEPTOR	**FA** (RA, QA)	?	H	?	?	TOUCH VIBRATION	–
RUFFINI ENDING	**SA II**	10-500 (59)	G,H	7 Hz	40-1500 μm (331 μm)	STRETCH SHEAR TENSION (?)	9 (15)
MERKEL'S CELLS	**SA I**	2-100 (11.0)	G	0.4-100 Hz (7 Hz)	7-600 μm (56.5 μm)	EDGE (?) PRESSURE	70 (8)
TACTILE DISKS	**SA**	3-50	H	?	?	?	–

Figure 4. Skin tactile receptors [9] SA-slow adapting, FA- fast adapting, I-small distinct field, II-large diffuse field, G-glabrous skin, H-hairy skin

3.2. Foundations of TENS

Transcutaneous electrical nerve stimulation involves delivering electric currents onto the skin through two or more surface electrodes connected to a stimulator. The usual parameters used for stimulation are 1-300 pulses per second and pulse width between 10 and 1000 μs. Naturally, lower signal amplitudes require higher pulse widths to reach sensation thresholds, and vice versa, as shown on Fig 5.

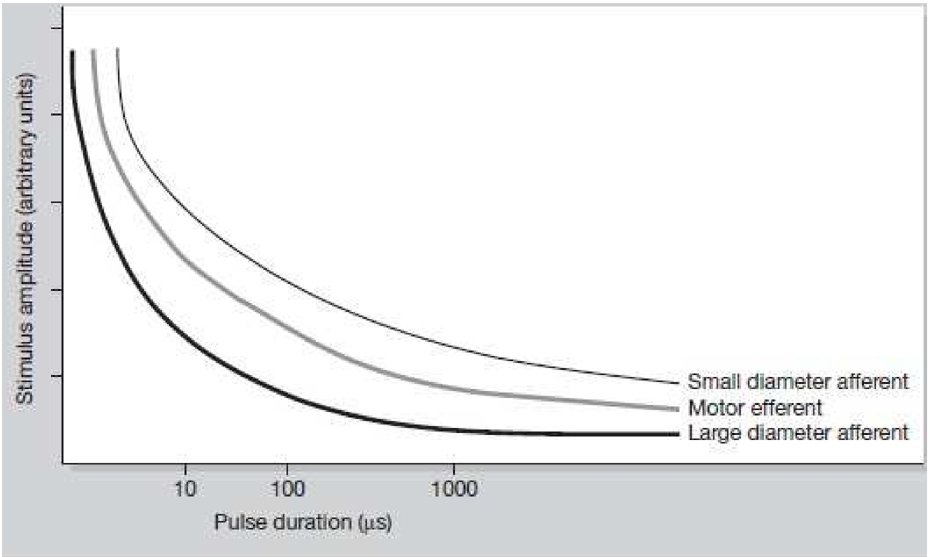

Figure 5. Activation of nerve fibers depending on the amplitude and pulse width of the applied impulses.

TENS parameters are chosen with the purpose of activating selectively different types of fibers. Fig 6. shows typical forms of TENS used.

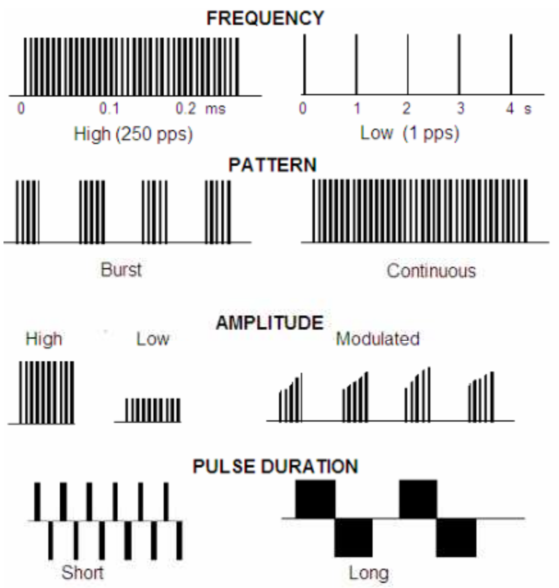

Figure 6. Typical TENS forms [1]

When using TENS, additional attention should be paid to the shape of the stimulation signals, not only their parameters. Typical signal shapes for TENS are shown in Fig 7.

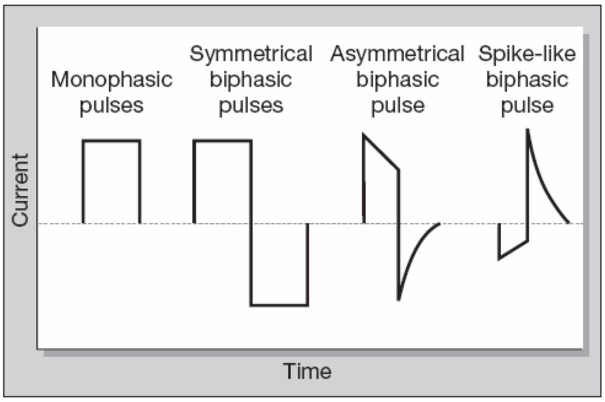

Figure 7. Typical signal shapes for TENS [1]

4. EXPERIMENTS

The experiments were conducted in the Laboratory for BioMedical Instrumentation and Technologies [2] at the Faculty of Electrical engineering in Belgrade, Offices of Tecnalia Serbia Ltd and the Orthopedic Department of the Clinical Center of Serbia. The experiments were performed in several steps, and as they progressed, the equipment used changed. The apparatus used in each step will be described separately.

4.1. Part I: Testing of various sensation qualities using a 3x4 matrix of concentric electrodes

4.1.1 Instrumentation

A squared matrix (9 x 7.5 cm) with 4 columns perpendicular to the direction of the forearm and 3 rows along the forearm was positioned on the forearm (Fig. 8). The matrix is formed by 12 small concentric electrodes (D=15mm) with the anode in the center and cathode on the perimeter. This electrode was produced by Tecnalia Serbia Ltd, Belgrade, Serbia. The matrix was covered with a single sheet of adhesive, conductive gel (AG702, AmGel, Axelgaard Manufacturing Co, USA) with narrow rings cut out of the gel between cathodes and anodes to avoid direct contact between the anodes and cathodes.

Each electrode was connected to a stimulator through a switchboard. The stimulator generated monophasic compensated pulses controlled online (pulse amplitude: I = 0 to 5 mA in steps of 0.1 mA, pulse rate: f = 8 to 400 pulses per second (pps) in steps of 8, pulse duration: T = 10 to 500µs in steps of 10 µs). The software controlling the stimulator was developed in the LabVIEW development environment. (Fig 9.)

[2] http://bmit.etf.rs/index.php?id=12

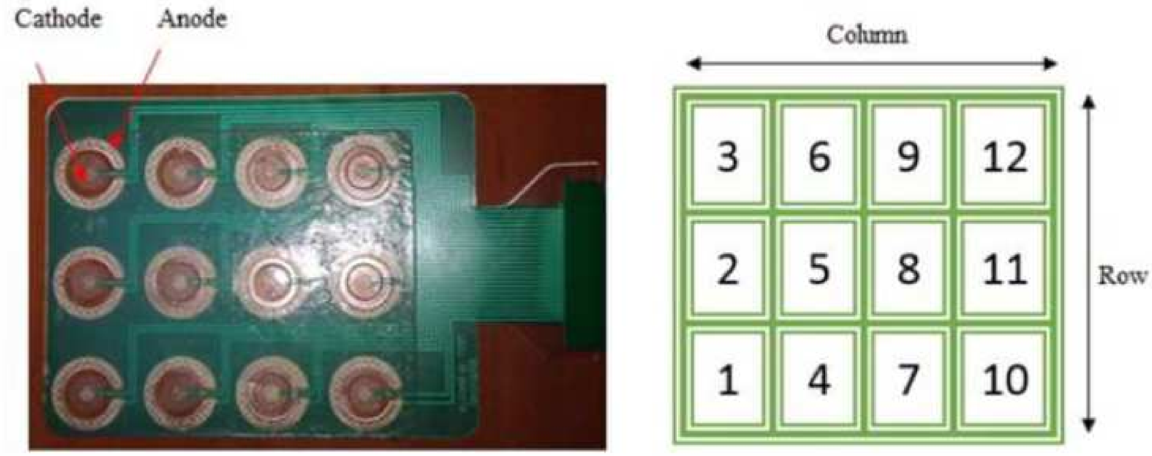

Figure 8. The matrix with 12 concentric electrodes (left) and the sketch of the annotation of the fields on the matrix (right).

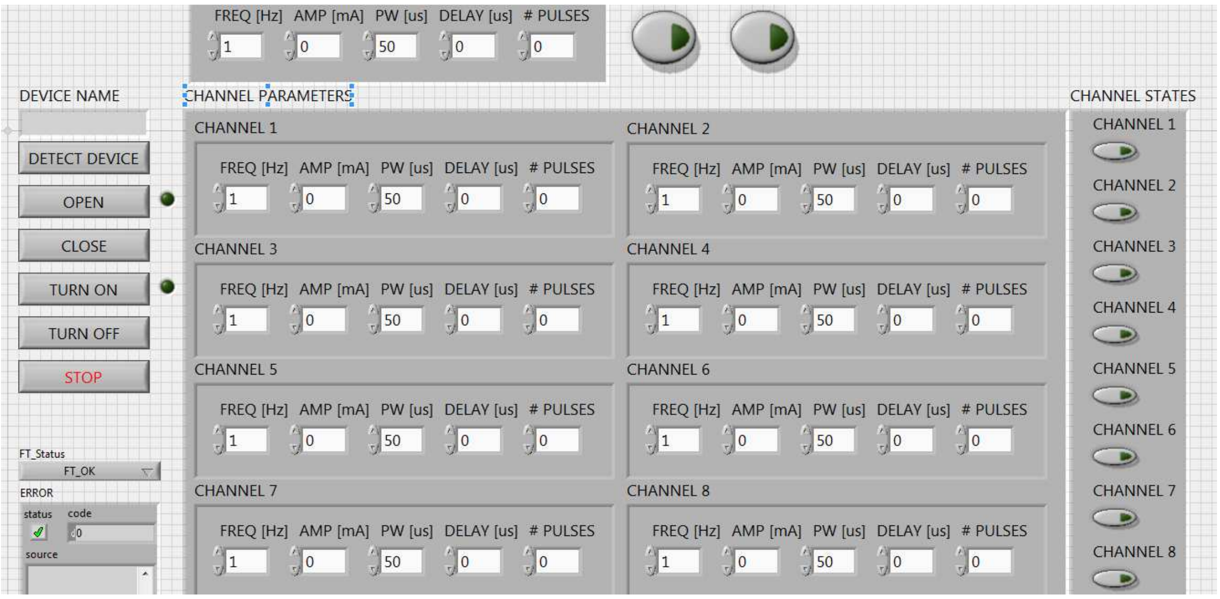

Figure 9. The program used for operating the stimulator, developed in LabVIEW.

4.1.2. Procedure

The tests were performed on 10 subjects, 4 males and 6 females, 12 through 45 years of age. Each subject was sitting with their right forearm relaxed on the desk. The top end of the matrix was positioned on the volar side of the forearm at about 30% of the forearm length from the elbow (Fig 10.).

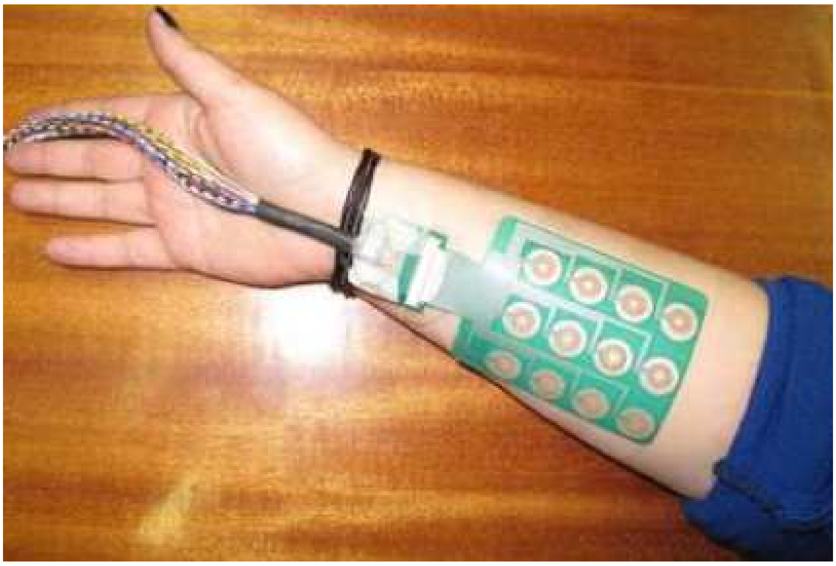

Figure 10. The matrix with 12 electrodes positioned on the forearm for measurements.

In the first test, the electrodes in the array were randomly activated. The subject was asked if he/she was able to distinguish which field (electrode) on the forearm was activated and to select among the following four sensations: very mild sensation, pleasant sensation, unpleasant sensation, and pain. The intensity of stimulation (pulse amplitude) at T =100 μs and f = 256 pps that led to a pleasant sensation was used in the continuation of the measurements. This pulse amplitude varied between subjects from 1.5 to 3.0 mA. In the second test, the subjects were asked to associate the elicited sensation with one of the seven modalities: 1) vibration, 2) touch, 3) pressure, 4) tingling, 5) tickling, 6) itching and 7) pinching. The analysis was done while changing the pulse rate and the charge per pulse (pulse duration).

4.1.3. Results

For each subject and each of 12 electrode fields, tables were generated as shown in Table 1. noting the sensation modality they felt for corresponding pulse duration and pulse rate of the applied signal. Each of the subjects reported sensations of at least four, and up to seven different modalities of sensation, depending on the pulse rate and the site on the matrix (field position).

Table 1 Sensation modalities reported by one subject for a single concentric electrode (field) activated at three pulse durations and eight pulse rates.

Field 1.	Pulse width			
		100	**200**	**300**
Pulse rate (pps)	**8**	Pinching	Vibration	Tingling
	64	Vibration	Vibration	Tingling
	120	Tickling	Vibration	Vibration
	176	Tickling	Itching	Tingling
	232	Itching	Tickling	Tingling
	288	Itching	Tingling	Vibration
	344	Vibration	Tingling	Tingling
	400	Tingling	Tingling	Tingling

Tables were also generated to observe the accuracy of distinguishing stimuli in space, as shown in the example in Table 2. For each electrode field, the perceived location of the stimulus was noted and compared to the actual location. If the location was accurately perceived, the number entered in the table would be 1. If the perceived location was not correct, but belonged to the same row (around the arm), the number would be 0.2, and if the location was not correct but belonged to the same column, the number entered would be 0.5. It should be noted that these numbers were arbitrarily picked for the sole purpose of differentiating these 3 cases, and convey no deeper meaning.

Table 2An example of a table created for one electrode field for one subject, depicting the accuracy of locating the origin of the stimulus. 1-exact, 0.5-correct column,but not row and 02-correct row but not column.

Field 1.		Pulse width (μs)			
Pulse rate (pps)	**8**	0.5	0.5	0.2	0.5
	64	0.5	0.5	0.5	0.5
	120	0.5	0.5	0	1
	176	0.5	0.5	0.5	1
	232	1	1	1	1
	288	1	1	1	1
	344	1	1	1	1
	400	1	1	1	-
		100	**200**	**300**	**400**

Summed over all subjects, dominance of vibration was noticed, followed by tingling and tickling. The subjects were also able to identify sensations of touch, itching, pressure and pinching, with itching being reported only seldom. The pie chart in Fig.11 shows the sensations most frequently reported for each field. This represents the occurrence of each sensation with respect to the total number of sensations.

When asked to pinpoint the location from which the stimulus originated, the subjects were most successful in correctly identifying stimulation coming from the borders of the electrode, and particularly the ones closest to the elbow crease. Fig. 12 shows the percent success rate in correctly locating the field that has been stimulated.

Figure 11 Most frequently reported sensations for each field, summed over all test subjects. The occurrence of each sensation is given in percent out of the total number of sensations reported, and colored differently.

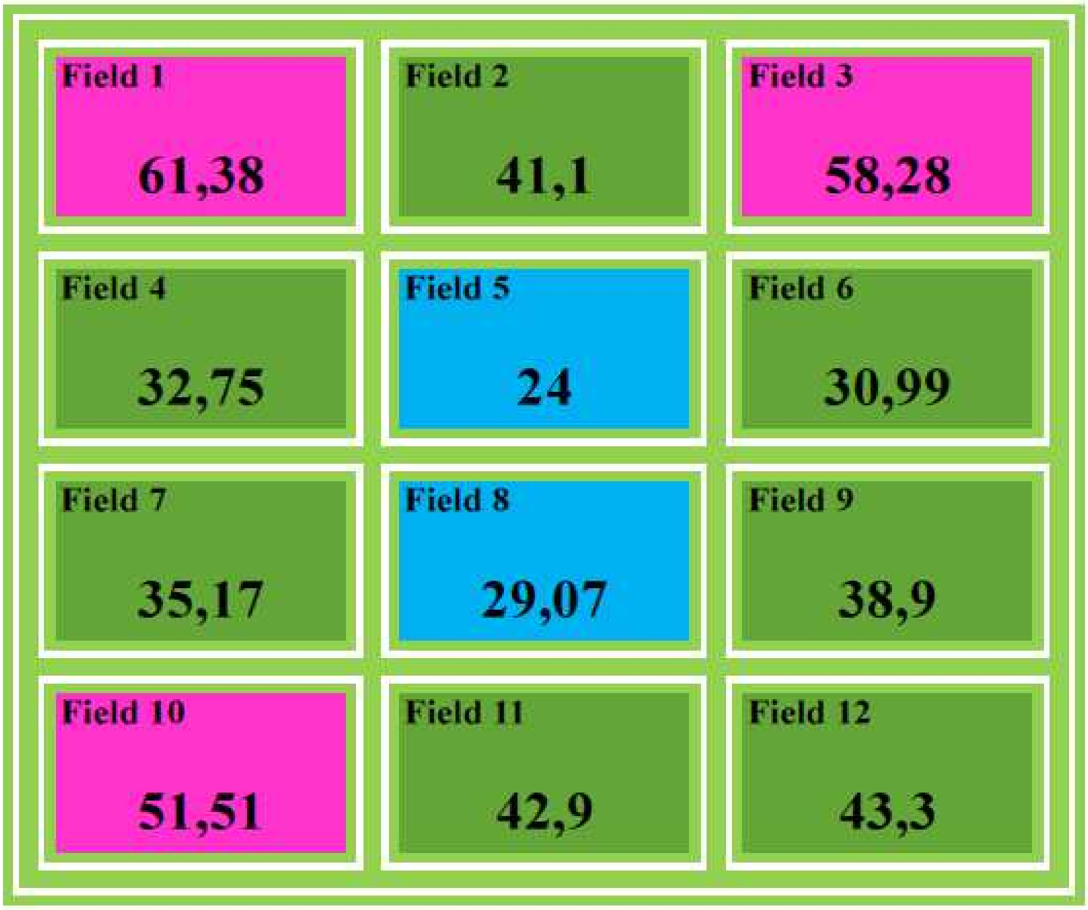

Figure 12 The success rate of correctly locating the site of the stimulus for all subjects.

The subjects were significantly more successful in pinpointing the origin of the stimulus when allowed to look at the electrodes. They had more difficulties to distinguish between the positions along the axial direction of the matrix compared with positions along the radial direction. Improvement was also noticed throughout the course of the session.

4.1.4. Discussion

This experiment demonstrated the ability of distinguishing sensations elicited by electrical stimulation on the forearm of healthy subjects, with regard to the pulse charge, pulse rate and position of the activated electrode. The inter-subject differences were significant; however it was clear that different stimulation parameters cause different sensations for all subjects.

The most frequently reported sensation was vibration, followed by tingling and tickling, with certain sensations being more dominant in one column of the multipad electrode than another. Namely, the sensation of touch was more common in column #1 (fields 1, 4, 7 and 10), the sensation of tingling slightly more present in column #2 (fields 2, 5, 8 and 11), whereas tickling was more often reported in column #3 (fields 3, 6, 9 and 12), and particularly on field #12.

Since the subjects had more difficulties distinguishing between the positions in the axial direction, it was concluded that a more suitable electrode for afferent stimulation would have a form that is circular around the forearm, as illustrated in Fig 13. This electrode was then used in the continuation of the study.

Figure 13 The new configuration of the multipad electrode for afferent stimulation.

4.2. Part II: Testing of the sensations and spatial accuracy of the perceived sensations using a circular 2x8 electrode

4.2.1. Equipment

In this part of the study we used the newly designed multipad electrode with 2 rows perpendicular to the axis of the forearm, with 8 cathodes in each row, and 7 anodes along the forearm (Fig 13.) and connected to an INTFES stimulator, which no longer required a computer program to operate, but instead had its own touch-screen display. The electrode was covered with a sheet of adhesive conductive gel, cut out between anodes and cathodes to prevent direct contact between them.

4.2.2. Procedure

The electrode was placed at about 30% of the forearm length from the elbow, with the connector facing the palm, and fields numerated as 15 and 16 lying next to the ulna. This part of the study tested only 2 subjects, who were asked to describe the sensations they felt and try to pinpoint the location the stimulation is coming from.

4.2.3. Results and discussion

Tables were created in the similar way as in Part I, for each subject and each field, noting the perceive quality and spatial origin of the stimulus. The various sensation modalities perceived were in accordance with the results of the first part of the study. However, the accuracy of the perceived location of the stimulus was still not on a satisfactory level. Therefore, we decided to continue the tests using only those fields of the electrode that formed a zigzag pattern, hoping this would yield higher precision stimulus locating.

4.3. Part III: Testing of spatial accuracy of the perceived sensations using a zigzag distribution of electrodes and the ability to memorize different sensations

4.3.1. Equipment

A multipad electrode with 2 rows perpendicular to the axis of the forearm, with 8 cathodes in each row, and 7 anodes along the forearm (Fig. 13) was placed on the forearm and connected to an INTFES stimulator. The electrode was covered with a sheet of adhesive conductive gel, cut out between anodes and cathodes to prevent direct contact between them.

4.3.2. Procedure

The electrode was placed at about 30% of the forearm length from the elbow, with the connector facing the palm, and fields numerated as 15 and 16 lying next to the ulna.

Tests were conducted on five healthy adult subjects, 3 females and 2 males. The amplitude of the stimulation signal was chosen so that it is well above the perception threshold to allow for easier distinction between qualities and locations of the induced sensations, and enough below the intensity that would cause any unpleasant sensations. Fields were activated in a random order, and the subjects were asked to pinpoint the location the stimulus is coming from. Since tests on 2 subjects showed that the percentage of correctly recognized locations of the stimulus origin was not satisfactory, the tests were conducted on all 5 subjects using only 8 out of 16 fields on the electrode – those forming a zigzag pattern starting from field No. 2 (Fields 2,3,6,7,10,11,14,15)

In the second test, the subjects were prompted to choose 3 fields on the multipad electrode, that they feel they can detect with least difficulty. Stimuli with two sets of parameters (number of pulses per second and pulse duration, ranging from 100 to 400 pps and from 200 to 300µs respectively), chosen according to the difference they make in produced quality of sensation, were then presented to the subjects for each field, and repeated several times. The subjects were asked to memorize the two different sensations these two sets of parameters caused for each field, in order to be able to recognize them later, when the field and parameter set were chosen and activated in a random fashion.

4.3.3. Results

For each subject a table was made as shown in Table 3. Correctly recognized fields in terms of location were signified as “1”, whereas those mistakenly identified are found in the table as “0”.

Table 3. Correctly and wrongly recognized fields in terms of location of the stimulus for one subject.

2 1	4	6 1	8	10 1	12	14 1	16
1	3 1	5	7 1	9	11 0	13	15 1

Summed over all subjects, and shown in percentages of correctly identified stimulus locations for each field out of all tests for that field, the results are presented in Table 4.

Table 4. Rate of correctly recognized stimulus locations summed over 5 subjects, expressed in % out of the total number of tests for the corresponding field.

100 2		**100** 6		**80** 10		**80** 14	
	100 3		**90** 7		**88** 11		**100** 15

After choosing 3 fields and attempting to memorize different sensations caused on those spots by signals of different pps and/or pw, for each subject we formed a table as shown in Table 3. To facilitate the learning process, the subjects were prompted to give names to the sensations felt as a result of the parameters used, or differentiate them by intensity.

Table 5. Correctly and wrongly recognized fields and sensations in terms of location and parameters used. "1" stands for the correct answer, and "0" for a wrong one. Some instances were tested several times, hence the varied number of ones and zeros.

Field number →	6	10	15
200us, 200Hz	Touch 1 1	Chills 1 1 1	Chills 1 1
300us, 300Hz	Chills 1 1 1 1	Vibration 1 1	Vibration 1 0 1

When the parameters were set appropriately, four our out of five subjects were able to memorize and correctly guess the spot and the parameters of the stimulation with no mistakes. One subject (whose results are shown in Table 5.) made one mistake, and identified all the rest correctly. One subject had trouble finding 3 fields they could differentiate well enough concerning the quality of sensation with different stimulation parameters, so only 2 fields were used for this learning test.

It was noticed that on low amplitudes of the signal, little above the perception threshold, the change of pulse width and pulse rate did not cause sensations different enough for the subjects to remember without direct comparison one right after another.

4.3.4. Discussion

This part of the study tested the ability of subjects to locate the origin of the stimulus using a multipad electrode with the tested fields chosen in a zigzag pattern. The test conducted on 5 subjects showed the rate of correctly identified stimuli locations, when fields of the electrode were activated in a random order, to be above 80%, and in the case of 4 fields this number raised to 100%, which led us to believe that this is the right configuration to use with the goal of establishing a form of feedback for patients with hand prostheses.

In the second part of the study, we chose for each subject two sets of stimulation parameters which gave the most recognizable differences in induced sensations, and asked the subjects to memorize these two sensations for each of the 3 chosen fields of the electrode, and try and answer where the stimulus is coming from, as well as which of the two sensations it is causing, i.e. which set of stimulation parameters is used. In almost all cases, this process of learning and recognizing went with no mistakes, suggesting that subjects could be trained to associate a certain sensation quality and/or intensity coming from a certain location with different information, such as low or high temperature of a grasped object.

However, due to technical difficulties accompanying the process of mounting electrodes with conductive gel on a person with their hand amputated, the next step we decided to take is conducting these experiments using electrodes with conductive rubber instead.

4.4. Part IV: Testing of spatial accuracy of the perceived sensations using a zigzag electrode distribution and the ability to memorize different sensations, conducted on an amputee

4.4.1. Equipment

This study involves testing of three multipad electrodes with 2 rows perpendicular to the axis of the forearm, with 8 cathodes in each row, and 7 anodes along the forearm, placed on the forearm and connected to an INTFES stimulator. One of the electrodes was padded with a thin layer of conductive rubber, another one with a thick layer of conductive rubber (Fig 14.), and the third one with a layer of conductive gel. Out of existing 16 fields on the electrode, we used 8 – those forming a zigzag pattern starting from field No. 2 (Fields 2,3,6,7,10,11,14,15)

Figure 14. Multipad electrodes used, coated with a thin (up) and thick (down) layer of conductive rubber.

4.4.2. Procedure

The experiments were conducted on one amputee subject, male, aged 60. The electrodes were placed as shown in Fig. 15. above the stump of the left arm.

Figure 15. Multipad electrode mounted above the stump and connected to a stimulator.

With each electrode, after determining the optimal current intensity, we performed the same two tasks:

1. Electrode fields were activated in a random order and the subject was asked to point at the location of its origin. This was then done with a different set of parameters (pps, pw), and the subject was asked to try and notice the difference between the first and second set of sensations.

2. Three of the 8 fields previously tested were chosen, and the subject was asked to memorize the different sensations caused by different stimulation parameters on those fields. After a short period of learning (two-three repetitions), the subject was asked to

identify the location of the stimulus as well as the parameters used (according to the intensity of the sensations they produced), when the order of fields activated and parameter sets were randomized.

4.4.3. Results

4.4.3.1. Electrode with a thin layer of conductive rubber.

The fields of tables below represent fields of the used electrode. Correctly recognized fields in terms of location were signified as “1”, whereas those mistakenly identified are found in the table as “0”.

Current intensity applied was set on **2.2 mA.**

Table 6. Accuracy of perceived location of the stimulus for 200us and 200 pps, tested on an amputee using an electrode with a thin layer of conductive rubber

2 1	4	6 1	8	10 0	12	14 1	16
1	3 0	5	7 1	9	11 0	13	15 1

Table 7. Accuracy of perceived location of the stimulus for 300us and 400 pps, tested on an amputee, using an electrode with a thin layer of conductive rubber.

2 1	4	6 1	8	10 1	12	14 1	16
1	3 1	5	7 1	9	11 1	13	15 1

It should be noted that the subject was, in a lot of cases, not able to point precisely at the location of the activated field, but rather had a sensation that spread a few centimeters along the forearm. Considering there is only one possible field in each column along the forearm, which the subject was aware of, this widespread sensation was considered a correct guess and represented in the tables as “1”.

The testing of 3 chosen fields after a short training yielded the following results (correctly and wrongly recognized fields and sensations in terms of location and parameters used. “1” stands for the correct answer and “0” for a wrong one. Some instances were tested several times, hence the varied number of ones and zeros.):

Table 8. Correctly and wrongly recognized fields and sensations in terms of location and parameters used. “1” stands for the correct answer, and “0” for a wrong one. Thin rubber layer electrodes tested on an amputee.

Field →	**3**	**7**	**14**
200us, 200Hz	11	11	11
300us, 400Hz	0011	11	0111

The subject was asked to contract those muscles of the tested arm that would have resulted in opening and clenching of the fist, or moving the thumb, had the hand been present, while electrical stimulation was applied. He reported feeling the stimulation while contracting the muscles.

To check if this action had an effect on the ability to recognize stimuli, we repeated the latest experiment, and got the results below.

Table 9. Correctly and wrongly recognized fields and sensations in terms of location and parameters used, after a series of deliberate muscle contractions.

Field →	**3**	**7**	**14**
200us, 200Hz	1	1	1
300us, 400Hz	1	1	01

The muscle activity didn’t seem to adversely affect the ability of recognizing the location and intensity of sensations caused by electrical stimulation.

4.4.3.2. Electrode with a thick layer of conductive rubber.

The same procedure was followed as with the electrode with a thin layer of rubber.

Current intensity was set on **2.3 mA**

Table 10. Accuracy of perceived location of the stimulus for 200us and 200 pps, tested on an amputee using an electrode with a thick layer of conductive rubber

2 1	4	6 1	8	10 1	12	14 1	16
1	3 1	5	7 1	9	11 1	13	15 --

Table 11. Accuracy of perceived location of the stimulus for 300us and 400 pps, tested on an amputee, using an electrode with a thick layer of conductive rubber

2 1	4	6 1	8	10 1	12	14 1	16
1	3 1	5	7 1	9	11 0	13	15 0

Table 12. Correctly and wrongly recognized fields and sensations in terms of location and parameters used. "1" stands for the correct answer, and "0" for a wrong one. Thick rubber layer electrodes tested on an amputee.

Field →	**6**	**10**	**14**
200us, 100Hz	1111	111	11
300us, 400Hz	1001	1110	101

4.4.3.3. Electrode with conductive gel.

Current intensity was set on **2.8 mA**

Table 13. Accuracy of perceived location of the stimulus for 200us and 100 pps, tested on an amputee using an electrode with a layer of conductive gel.

2 1	4	6 1	8	10 1	12	14 1	16
1	3 1	5	7 1	9	11 1	13	15 --

Table 14. Accuracy of perceived location of the stimulus for 300us and 400 pps, tested on an amputee using an electrode with a layer of conductive gel.

2 1	4	6 1	8	10 1	12	14 1	16
1	3 1	5	7 1	9	11 1	13	15 --

Table 15. Correctly and wrongly recognized fields and sensations in terms of location and parameters used. "1" stands for the correct answer, and "0" for a wrong one. Gel coated electrodes tested on an amputee.

Field →	**3**	**7**	**11**
200us, 100Hz	11	1	1
300us, 400Hz	11	10	11

During the experiment it came to accommodation to the stimulation, so the last test (with the chosen 3 fields) was conducted using the current amplitude of **3.2mA**. In addition, field No. 7 had to be "reset" by means of a short stimulation of the field with the current amplitude of **5mA**.

4.4.4. Discussion

This part of the study came as a result of previous preliminary studies on healthy subjects, which implied the possibility of training subjects to associate a certain sensation quality and/or intensity coming from a certain location with different information, such as low or high temperature of a grasped object. Here we repeated the same protocol on an amputee, and found no significant differences from healthy subjects, except that the sensations seemed to be more spread in the direction of the forearm than in the case of healthy subjects.

Three multipad electrodes were tested, coated with a thin layer of conductive rubber, thick layer of conductive rubber and a layer of conductive gel, in that order. The subject was asked to locate the stimulus origin, and then to try and memorize the different sensations caused by different stimulation parameters (pps,pw) on 3 chosen fields.

Each electrode yielded a satisfactory percentage of correctly recognized stimuli locations (81%, 86%, and 100% respectively), as well as a satisfactory percentage of correctly recognized location and stimulation parameters used (80%, 81% and 90%).

The electrode with a thick layer of gum produced slightly more unpleasant sensations than the other two electrodes, and the process of learning to recognize sensations produced with it took slightly longer.

The electrode with conductive gel gave a higher percentage of correctly localized fields and recognized stimuli parameter sets. Accommodation to electrical stimulation was present with this electrode, but possibly as a result of tests with all 3 electrodes being performed consecutively.

Contracting muscles of the tested arm did not adversely affect the ability of recognizing the location and intensity of sensations caused by electrical stimulation.

4.5. *Part V: Testing of the ability of healthy subjects to associate different sensations with pictures shown on the screen*

4.5.1. Equipment and procedure

A circular 2x8 electrode coated with a thin layer of conductive rubber was placed on the subjects' forearm, at about 30% of the forearm length from the elbow crease. Three of the existing 16 fields were chosen and activated.

For this part of the study we took pictures of 3 types of grasps and two sizes of grasped object for each of them. (Example on Fig 16) The pictures were shown to 3 healthy subjects as they received stimulation on an a priori chosen location and with certain parameters of stimulation, and they were asked to associate the quality and/or intensity of the elicited sensation with the corresponding picture, and memorize that connection. After the subjects reported feeling confident about knowing which stimulus corresponds to which image, the screen was taken away, and they were asked to name the picture they thought of once a stimulus was applied to their forearm in a random fashion. The stimulation parameters were chosen to fit intuitively to the pictures, i.e. small objects were presented through a stimulus that caused a lower intensity perceived sensation than large objects.

Figure 16. Example of the pictures used. This one shows a palmar grasp of a small object.

4.5.2. Results

For each subject we created a table such as table 16, showing whether the stimulus applied was correctly associated with the corresponding image that was presented to the subject during the course of the training.

Table 16. Correctly and wrongly recognized fields expressed through the associated image. "1" stands for the correct answer, and "0" for a wrong one.

Grasp →	**Palmar grasp**	**Palmar pinch**	**Lateral pinch**
Small object	111	111	111
Large object	110	10111	111

4.5.3. Discussion

In total, the subjects responded correctly in 83.02% of cases. The wrong guesses were due to the difference of perceived intensities for the same object size (small/large) on different locations. To be more precise, the same actual stimulus intensity caused two different perceived intensities when applied on two different fields. This can probably be surpassed by choosing the stimulation fields more carefully.

5. CONCLUSIONS

The first step of this study was to test the ability of healthy subjects to discriminate perceived sensation modalities elicited through the use of a 4x3 matrix of electrodes coated with a layer of conductive gel. The results showed significant inter-subject differences, but undoubtedly point to the fact that different durations and rates of the pulses used cause different qualities (and/or intensities) of the sensations on the forearm of the subjects, considering that all subjects reported feeling at least 4 and up to 7 different sensations, such as itch, pressure, vibration, tingling, etc.

The ability to discriminate the stimuli in terms of the location was also tested, and it was shown that the best accuracy rate was achieved on the corners of the matrix, and that it was easier to discriminate stimuli in the radial than axial direction.

Thus we chose to perform these tests again, but using an electrode matrix that was circular, i.e. had only two rows of electrodes wrapped around the forearm. The perception of different sensation modalities was unchanged, but the spatial discrimination was lower than expected, so further experiments were conducted using a zigzag configuration of electrode fields. This yielded satisfactory results with regard to the ability to spatially discriminate origins of the stimulus. (Part III)

Part III of the measurements involved a test to see whether subjects could learn to memorize different sensations elicited by stimulation on different fields and with different signal parameters. Though the spatial-discrimination results suggest that this would be possible for all 8 fields in the zigzag pattern, this would have been highly time-consuming, so the memorization tests included 2 sets of parameters applied onto 3 different locations on the forearm. As expected, the subjects were always sure about the location of the stimulus, but in rare cases confused the intensity/quality of the applied stimulus.

For the convenience of mounting, we tested two electrodes coated with a thin and thick layer of conductive rubber, and together with an electrode with adhesive gel, tried them on an amputee subject. (Part IV) The results were no different than those obtained from the healthy subjects.

The subject was able in most cases to correctly recognize the location and intensity/quality of the elicited sensation compared to the actual one.

The electrode with a thick layer of gum produced slightly more unpleasant sensations than the other two electrodes, and the process of learning to recognize sensations produced with it took slightly longer.

The electrode with conductive gel gave a higher percentage of correctly localized fields and recognized stimuli parameter sets. Accommodation to electrical stimulation was present with this electrode, but possibly as a result of tests with all 3 electrodes being performed consecutively.

Contracting muscles of the tested arm did not adversely affect the ability of recognizing the location and intensity of sensations caused by electrical stimulation.

Encouraged by these results, we took a step further and in Part V asked (healthy) subjects to memorize the picture on the screen showing one of 3 types of grasps and one of 2 sizes of objects when a certain set of parameters was used to elicit sensation on a certain, a priori chosen field. The subjects responded correctly in 83.02% of cases, suggesting it would be possible to implement a system that would stimulate a certain spot and cause a specific sensation on it consistently when an object of predefined size range was grasped through a predefined grasp, giving thus the subject a feedback, without having to always look at the object being held. This is expected to make the patients feel more comfortable using a prosthetic hand, and experiencing it more as a part of their own body.

It remains to be determined just how exactly the electrodes and the stimulator are to be mounted on a patient's arm. The number of needed electrode fields depends on the desired number of messages to be delivered (next to the type of grasps this might involve hot/cold or tight/loose information). If the desired number of electrodes is small, the configuration need not be a matrix, but separate electrodes that would be placed on independent, meticulously chosen spots so that they cause perception of most pleasant and most easily recognized sensations. If the number of electrodes is larger, they should be placed in a zigzag pattern around the forearm. The increase in the number of possibly activated fields increases the training time.An option would also be mounting electrodes on the upper arm of the patients. This is expected to give similar results as the forearm, but requires testing.

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