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COSTaM: Tool Design for a Controlled Tactile Stimulation

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Abstract

Tactile stimulation is used in the rehabilitation of damage to the central or peripheral nervous system and in brain injury recovery. Tactile deficits of the hand are currently diagnosed through the evaluation of pain thresholds, spatial discrimination, vibration sensitivity and by using filaments or tuning forks, without truly established protocols. The global goal of the COSTaM project is to develop a tactile stimulator to identify tactile disorders and allow specific rehabilitation. The first step is to study the response of healthy individuals to complex textures in different ways: perceptive discrimination, study of friction and vibration between textures and the finger and the response of each kind of cutaneous mechanoreceptor. Three kinds of real textures have been chosen: *relief*, *braking* and *fibrous*. The use of a tactile stimulator, based on the modulation of the coefficient of friction with the finger, has been validated for the simulation of the *braking* descriptor.

Key words

Tactile disorders, tactile stimulator, finger, touch, cognitive psychology, biotribology, microneurography, mechanoreceptors.

1. Introduction

A major part of tactile sensibility disorders comes from the impairment of the central nervous system, often following a cerebral vascular accident (stroke). Stroke is the second leading cause of mortality in the European Union. In France in 2010, there was "1 stroke every 4 minutes" (1). The damage may be motor, sensory and/or behavioural. Approximately 50-60% of stroke survivors suffer from a loss of sensitivity, especially touch.

Due to an increase in life expectancy, French people are getting older. The number of people more than sixty years old will drastically increase and will represent 31% of the population in 2035, against 22% today (2). Aging is a cause of loss of touch sensibility through the normal injury of the peripheral nervous system, which starts after 25 years of age with skin aging.

A change or a diminution of tactile sensibility is frequently found with multiple sclerosis (MS), the most common disabling neurological disease in young adults. It is estimated that one third of patients taken into rehabilitation centres suffer from a loss of touch. In France, 80 000 people are currently suffering from MS, with 4000 new cases every year.

In 2009, 4.4% of the French population were treated for diabetes, against 2.6% in 2000 (3). Diabetes causes neuropathies, including of the upper limb. Moreover, there are 1 400 000 accidents involving the hand per year (15% of the total of everyday accidents and 38% of the accidents at work) (4) and these are accompanied by nerve damage in 40% of cases. The use of vibrating tools (e.g. drills) may lead to musculoskeletal disorders (MSDs) and touch impairment. They represent more than 80% of occupational diseases recognised in France (5).

These considerations reflect the significance of the loss of autonomy encountered by patients with tactile sensibility disorders and the numerical importance of the affected population. The consequences of tactile disorder include difficulties feeling and distinguishing stimuli, and an increase in reaction time leading to a decrease in the ability to grasp and handle objects, to differentiate textures, to write or type on a keyboard, and to use common objects. Tactile stimulation is widely used in the rehabilitation of damage to the central or peripheral nervous system, based on knowledge of the mechanisms of plasticity in the central nervous system and of brain injury recovery. It is administered through massage, the exploration of textures, or through the manipulation and palpation of objects with varying textures and shapes. Tactile deficits are currently diagnosed by evaluations of pain thresholds, spatial discrimination, vibration sensitivity and by using filaments or tuning forks, without truly established protocols or normative data. The COSTaM project is aimed at patients with a loss of tactile sensibility, in order to help them recover some of their autonomy or to slow down the advance of the disorder. The global goal is to develop a tactile stimulator to identify and estimate tactile disorders and allow specific rehabilitation. Firstly, the complex textures used for this project had been to be chosen. Secondly, the response of healthy individuals to textures had to be studied in various ways: perceptive discrimination, study friction and vibration between the textures and the finger, and the response of each kind of mechanoreceptor. Finally, a tactile stimulator able to simulate real textures, but programmable by therapists, had to be designed.

2. Experiments

2.1 Real texture investigated and test protocol

Three kinds of real textures have been chosen because they embody tactile descriptors identified as significant descriptors in perceptual space representation (6, 7), and, as recommended by the literature, they should excite the different kinds of cutaneous mechanoreceptors (8). For the *relief* descriptor (smooth - rough) each asperity stimulates a small receptor field for the excitation of Merkel cells. For the *braking* descriptor (slippery - sticky), the skin surface is deformed, stretched and should be excited the Meissner and Ruffini corpuscles. For the *Fibrous* descriptor (without or with hairiness) each bristle moving on the skin surface creates a brief stimulation and is convenient for the rapidly adapting mechanoreceptors, the Pacinian, and Meissner corpuscles.

Different intensity gradients have been chosen (9), and are quantified from 0 (low level) to 100 (high level). The quantification was carried out previously by one of the co-authors, Expertisens, with a trained sensorial panel. These different gradients are proposed by all the partners of the consortium for healthy individuals. Different types of analysis are processed: perceptive discrimination, tribological behaviour in terms of finger friction force, and vibration or individual signals of cutaneous mechanoreceptors.

A protocol was established by the partners to describe the experimental conditions used to introduce the different gradients of the three descriptors to individuals. The protocol fixes the experimental conditions: the right forefinger is investigated, it is cleaned with a hydroalcoholic gel, the normal force on the rubbed surface is 0.5 N, the sliding speed is about 20 mm.s^{-1} and the sliding distance is 40mm, the angle between the finger and the surface is 25°.

2.2 Presentation of the tactile stimulator

A tactile stimulator is a programmable device which simulates the feeling of a texture. It can give the user the illusion of touching a smooth or a textured surface, depending on the programme. In this project, the main tactile stimulator considered was the STIMTAC (10). It is based on the modulation of the coefficient of friction between the finger and the touchpad of the stimulator due to low amplitude vibration (a few microns) at a frequency too high to be detected by cutaneous mechanoreceptors (11).

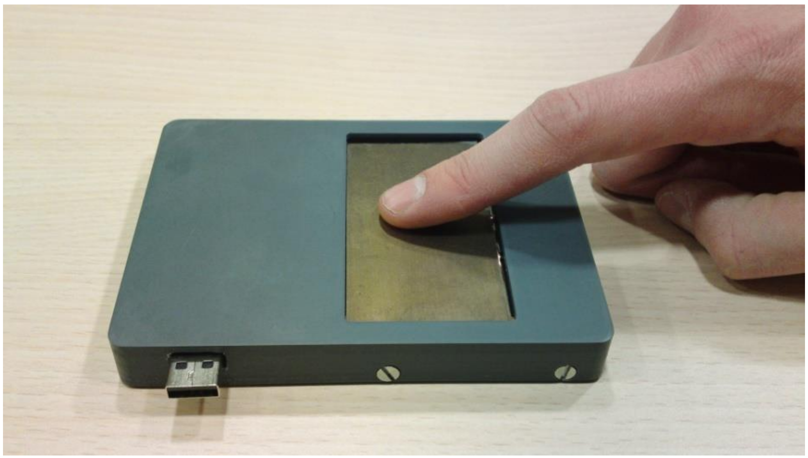

Fig. 1: The tactile stimulator STIMTAC.

The resulting tactile effect is similar to lubrication. It is then necessary to change the friction in order to simulate textures. For that purpose, the position of the fingertip on the plate is measured in real time, and the vibration amplitude of the plate is changed according to this position (Fig. 1). The textures which can be simulated may be grooved surfaces, as in (12), or more complex surfaces such as the textile fabrics in (13).

2.3 Psychophysical analysis

This study aimed to assess the sensitivity of the dominant hand's forefinger to different textures, instantiating the single descriptors previously determined (*relief*, *braking*, *fibrous*) and their intensity gradients (very low, low, moderate, high and very high), preselected on the basis of results obtained from pilot investigations. A total sample of 24 adults (F = 16, M = 8) participated in this experiment. Two age groups were formed: less than 35 years of age (n = 12, mean age = 28 years 8 months, range: 22-35 years) and more than 35 years of age (n = 12, mean age = 51 years 3 months, range: 36-70 years). Participants were predominantly right-handed (23 right-handed and one left-handed). None suffered from physiological or cognitive deficits that might alter their tactile perception or judgment. Materials consisted of 14 textured squares (4.5 x 4.5cm) reproducing five intensities for the *relief* and *fibrous* descriptors and four for the *braking* texture.

The procedure started with a training phase during which the participants were introduced to the tasks using the standard exploration technique described in Section 2.1. During this session, the participants explored the first type of texture with intensities presented in ascending order, then they performed a ranking-test for each of the four or five intensities presented in a random order, using a visual reference (Likert scale), symbolising the intensity gradient range. This procedure was repeated for each intensity and for the two other types of texture. Finally, the participants self-evaluated their touch sensitivity on a 0-to-3 scale, 0 being "not sensitive at all" and 3 "very sensitive". The experimenter then captured the digital fingerprint in the conditions of standard exploration.

For each participant, we calculated the discrepancy between the objective rank and the ranking-score attributed to each intensity within each type of texture. Mean scores were computed for the absolute and relative (positive and negative) score values. Mean absolute scores were used for quantitative analysis (magnitude of error), while the relative values provided qualitative information (over- or under-estimation). ANOVAs including inter-age and gender as between-subject factors, and type of texture as a within-subject factor were conducted on the mean ranking error. For each texture, ANOVAs including inter-age and gender, and intensity as a within-subject factor, were conducted on the mean score of ranking error. Student's t-tests completed the ranking error analysis. Finally, Pearson correlations were computed between the participant characteristics (fingerprint size, sensitivity score) and their ranking scores.

2.4 Tribological analysis

Two tribological approaches were taken: to correlate the friction signal characteristics to rubbed surfaces and to correlate finger characteristics to friction signals.

The first approach focused on the role, in the surface properties, of both the macroscopic friction coefficient variation and the vibrations induced by the scanning of the fingertip on the touched surface. The analysis is developed on three intensity gradients (very low, moderate and very high) of the three descriptors: *braking* and *relief* descriptors are isotropic and are thus tested by scanning the fingertip along one direction; samples from the *fibrous* descriptor are anisotropic and are scanned in two orthogonal directions. The measurements have been performed using the TRIBOTOUCH tribometer (Figure 2) (14, 15).

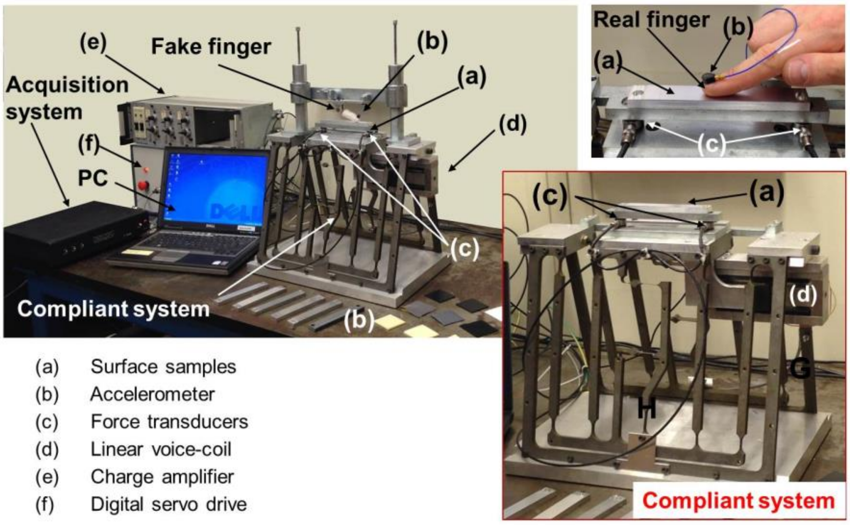

Fig. 2: The TRIBOTOUCH set-up (14, 15).

The acceleration at the fingernail, and the normal and tangential (frictional) forces are recorded during the surface scanning, in which the relative velocity is constant, and are kept for analysis. The frequency spectra of the acceleration signals are analysed. The mean values of normal and tangential forces and their weighted standard deviation (WSD) are calculated. The root mean square (RMS) of the acceleration is also calculated. Three individuals participated in this experiment.

The aim of the second study was focused on the correlation between a human subject's forefinger properties and the friction signals recorded when it slides on two *braking* surface gradient intensities (very low and very high). These two braking intensities are performed with both real surfaces and with virtual surfaces of the same kind programmed on STIMTAC. A total of 26 adults subjects (F = 13, M = 13) who were from 34 to 57 years old (mean age = 42) performed both friction tests and forefinger surface characterisation. None suffered from physiological or cognitive deficits that might alter their tactile perception.

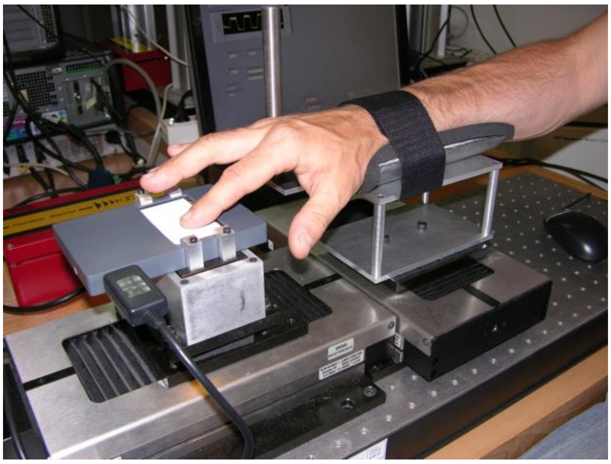

Fig. 3: Tribometer allowing frictional response signal measurement of finger sliding on a braking surface, simulated with STIMTAC.

Finger surface characteristics were evaluated with: Fourier-Transform InfraRed spectroscopy (FTIR) to characterise the forefinger hydrolipid film composition, a specific indentation device for finger rigidity measurement, and 3D confocal microscopy for surface forefinger shape and topography characterisation. Friction tests were performed with a specific laboratory-made tribometer (Figure 3) carrying out coefficient of friction (COF) measurements of subjects' forefinger in contact with both real and virtual surfaces. The frictional criteria retained to assess the subjects' frictional discrimination between more or less braking or sliding surfaces is called the contrast. Assuming COF0 and COF90 are respectively the means COF measured with very high low and very highly braking surfaces, contrast is then calculated as follows:

$$Contrast = 1 - \frac{COF_0}{COF_{90}} \quad (1)$$

2.5 Microneurography

The microneurographic technique consists of recording the neural activity of peripheral nerves in conscious human subjects. This technique was introduced by Vallbo and Hagbarth (16). In theory, microneurography can be performed on any peripheral nerve but it is most commonly applied to superficial nerves: the common peroneal nerve at the leg level or the median, ulnar, and radial nerves at the arm level. A microelectrode with a tip diameter around 5µm is manually inserted percutaneously into the peripheral nerve by alternating light pushes and releases. Once the microelectrode reaches the nerve, it is moved in minute steps until the activity of a single sensory fibre (afferent) is isolated. The nature of the afferent is then identified and the related receptor is located. For cutaneous afferents, the innervated skin area (receptive field) is first coarsely located by lightly brushing the skin. The force threshold and the boundaries of the receptive field are then defined using calibrated nylon monofilaments. The receptor adaptation properties, that is to say the ability to encode the occurrence or the permanence of a pressure, are similarly defined using nylon monofilaments.

3. Results

3.1 Perceptual discrimination

The psychophysical analysis revealed a significant effect of the type of texture, $F(2, 40) = 29.86$, $p < .01$, the *relief* texture being better ranked (mean ranking error = .19) than the *braking* (.32) and the *fibrous* textures (.79). Age and gender factors failed to show any significant effects, $Fs < 1$, while intensity reached significance, $F(4, 80) = 7.19$, $p < .01$, indicating very accurate ranking for extreme intensity values (1 and 5), while intermediate values (2 and 4) obtained moderate ranking error scores, respectively .22 and .31. The median intensity value 3 was the least accurately ranked (.44). The pattern of results (ranking error) thus depicted an inverted U shape as the function of intensity increased for the *relief* and *braking* textures, confirmed by significant and marginal quadratic effects, respectively $F(1, 20) = 14.2$, $p < .01$ and $F(3, 60) = 2.21$, $p = .097$. Similar analysis conducted on the *fibrous* texture did not reveal any significant effects, $Fs < 1$, however, the qualitative analysis showed a reverse pattern of results for the *fibrous* texture, as compared with those observed for other textures. Participants mostly overestimated the extreme lower intensity and underestimated the uppermost intensity of the *fibrous* texture. Student's t-tests confirmed that only the ranking error scores for these extreme intensities significantly differed from zero (theoretical value proving the absence of error), respectively $t(23) = 3.84$, $p < .001$ and $t(23) = -5.36$, $p < .0001$). Finally, the very low Pearson correlations did not provide evidence of interrelations between footprint size, self-reported sensitivity, and ranking performance in this task.

3.2 Tribological and vibration analysis

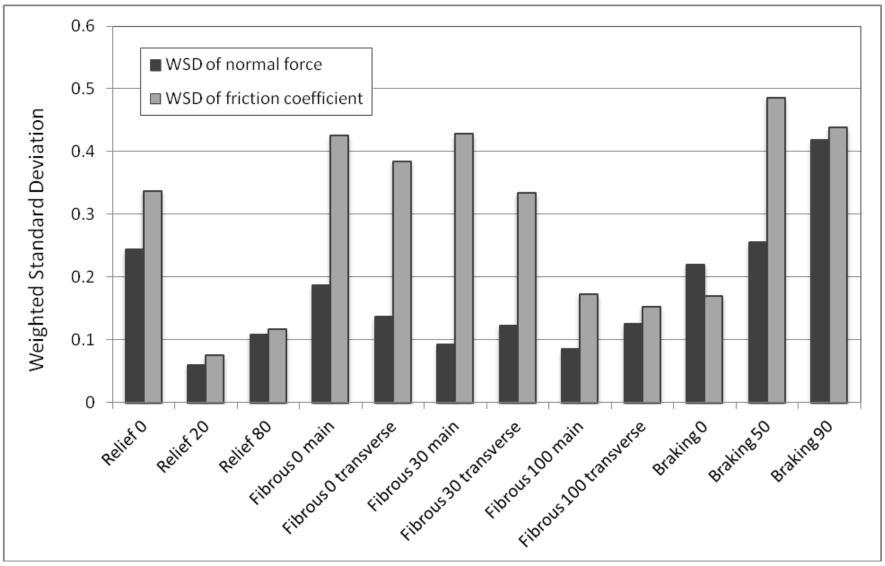

Fig. 4: Weighted standard deviations (WSD) of COF and normal force for the three descriptors: *relief* (gradients 0, 20, 80), *fibrous* (intensity 0, 30, 100) along the main and transverse directions, and *braking* (intensity 0, 50, 90).

The objective of the first tribological examination was to find possible correlations between characteristics (objective indexes) of the vibrational and tribological signals and the properties of the tested surfaces. The mean value of the friction coefficient provides information about overall frictional resistance, while its weighted standard deviation (weighted with the mean) and the root mean square of the acceleration provide information about the time variation of friction and skin deformation, due to the roughness of the surfaces on contact or/and to stick-slip phenomena due to adhesion.

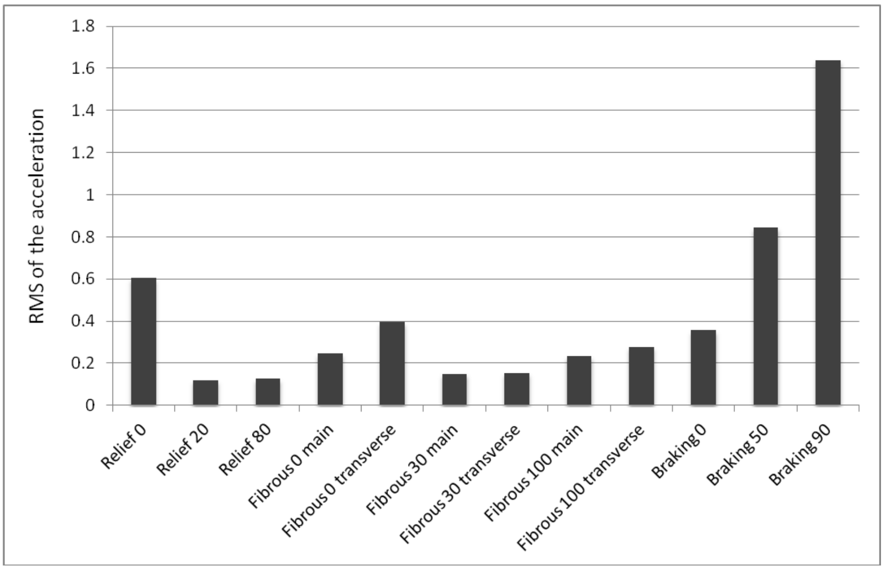

Fig. 5: RMS of the acceleration related to both roughness and adhesion phenomena.

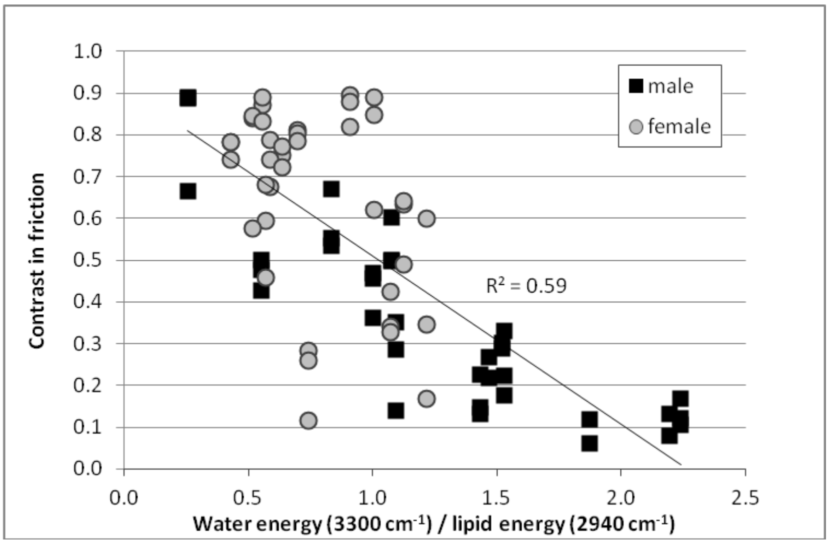

Fig. 6: Relationship between contrast in friction and the integrated energy peak due to O-H bonding stretching vibration mode (water related) against C-H bonding asymmetric stretching vibration mode integrated energy peak (lipids related).

Figure 4 shows the weighted standard deviations of both COF and normal force. Figure 5 shows the root mean square of the acceleration. Results on *braking* surfaces show that when the *braking* effect increases (from 0 to 90), the adhesive feature, highlighted by the stick-slip behaviour, increases. The same trend is similar for the WSD of the normal force and the RMS of the acceleration. Results from the *relief* surfaces indicate an increase of the indexes (WSD and RMS) with the descriptor intensity between 20 and 80, while the results for the 0 intensity indicate that the roughness (relief) is not the only factor affecting these measures. The same is highlighted for the *fibrous* descriptor.

The experiment was intended to find correlations between finger characteristics and friction signals. Firstly, the coefficient linking the contrast obtained from the real *braking* surfaces and from the *braking* simulation from STIMTAC was 1.09 with a coefficient of determination of 0.73. Secondly, no strong correlation was found between shape, topography or rigidity of the finger surface and contrast measurements, whereas contrasts measured are well correlated with the water versus lipids proportion present on the forefinger surface (Fig. 6). A clear distinction between female and male subjects is noted.

3.3 Individual responses from tactile mechanoreceptors

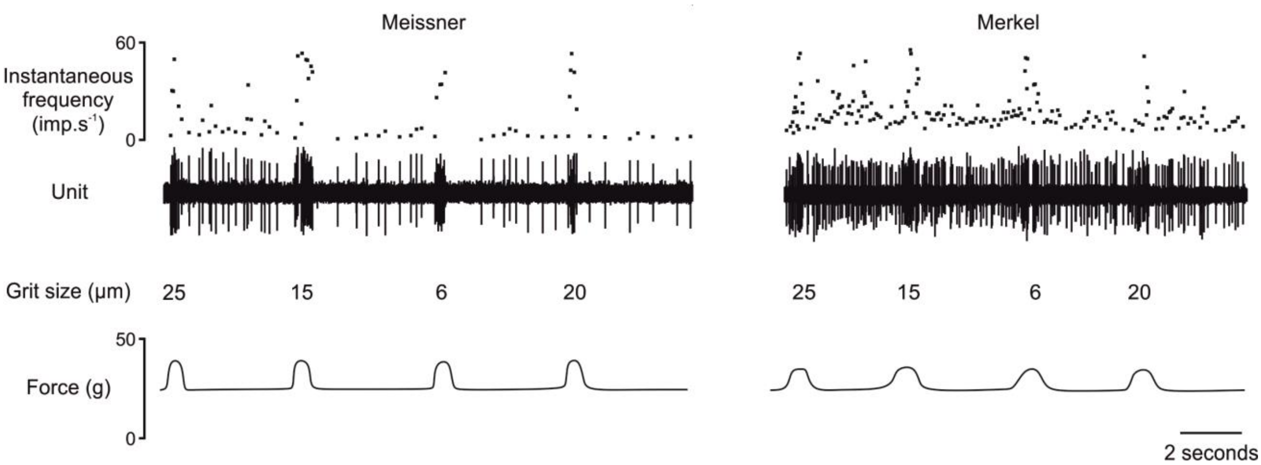

Fig. 7: Microneurographic recording of a Meissner (left) and a Merkel (right) cutaneous afferent from the extremity of the index. The afferents responded to skin stroking here with 6 to 25µm sandpapers.

The COSTaM project required the adaptation of both the microneurographic technique and the tactile stimulation device to the hand, since recording directly from the hand has never before been done in France. The recording of tactile afferents from mechanoreceptors located in the glabrous skin of the hand, by inserting a microelectrode into the median nerve, has been successfully done in 2013 and up to 20 afferents have been recorded so far. As an example, Figure 7 illustrates the encoding of roughness by two afferents coming from mechanoreceptors with small receptive fields, one fast adapting Meissner unit (left) and one slow adapting Merkel unit (right). The afferents were stimulated with sandpaper with grit size ranging from 6 to 25µm. , The frequency of discharge increased with grit size for both fibres.

3.4 Electrovibration with STIMTAC

The stimulation capabilities of STIMTAC were enhanced by coupling it with another mode of friction modulation. Electrovibration consists of electrostatic forces generated between the fingertip and the stimulator, and was introduced in a revised version of STIMTAC. Coupling electrovibration with the air gap generated from the plate vibrations was achieved on a tactile stimulator for the first time on STIMTAC. The prototype allowed us to study the cooperation of the two stimulation principles. It is built up with a vibrating tactile stimulator associated with a high frequency- low voltage power source, and a high-voltage low frequency power amplifier for the electrovibration. This hybrid tactile stimulator has shown that merging the two tactile effects induces a more contrasted stimulation which will ultimately allow a more accurate simulation.

Conclusion

The first results from the COSTaM consortium, as described in this paper, essentially involves setting up the tools for the global goal of developing a tactile stimulator to identify and estimate tactile disorders and allow tactile rehabilitation specific to each patient.

Textures are chosen corresponding to three of the tactile descriptors identified as significant in perceptual space representation and able to excite the four types of cutaneous mechanoreceptors: *relief*, *braking* and *fibrous*. An experimental protocol was defined by the consortium to present the surfaces to individuals. The results obtained from the perceptive discrimination and the tribological and vibration analysis show that some real surfaces, the intensity gradients, corresponding to *relief* and *fibrous* descriptors, have to be redefined. The results obtained for the *braking* descriptor are promising. In fact, gradients have been correctly discriminated and the correlation between finger friction and vibration, and the gradients have been highlighted. The tactile stimulator used has been validated for *braking* descriptor simulation.

Acknowledgments

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