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Abstract

Recognition of texture properties requires sliding contact between finger and object surface. Although it is well known that vibrations stimulate the tactile afferents, the mechanism by which Friction-Induced Vibrations (FIVs) interfere with tactile perception is still unknown. As well, the role of mechanical stimuli on hedonistic feedback from the touched surface is unknown. Correlations between surface features and perception are here examined, while the analysis of the mechanical stimuli, which are the direct elements of activation of the human receptors, is performed. Two different sensory analyses are exploited: hedonistic perception and perception dimension categorization. The analysis of the frequency and amplitude of the FIVs, allowed for explaning the correlations between the perception analyses and the topography characteristics of the samples.

Keywords: tactile perception, friction-induced vibrations, hedonistic perception, textures

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1. Introduction

Human kind perceives and feels the external world through the five senses. Although they act coupled to supply the external reality, each of them represents a specific channel able to decode a specific information. To have experience about the different object properties, like material or topographic features, the contact is needed and we entrust to the tactile sense. The tactile perception process begins with the codification, as electric pulses, of the mechanical and thermal stimuli produced in the contact region. This task is fulfilled by the tactile transducers that, innervating the skin, are close to the contact. Finally, the electric pulses are sent to the brain by the nervous system, where the signal is processed to the perception. The mechanoreceptors are made by different afferents fibers, which are distinguished in Pacinian corpuscles, Ruffini endings, Meissner's corpuscles and Merkel disks [1] [2]. They are classified, based on their speed of adaptation with respect to the mechanical stimuli, in slow adapting receptors (SA) and rapidly adapting receptors (RA). While the SA receptors are able to detect constant mechanical stimulus like pressure and skin stretch, the RA receptors allow the detection of transient mechanical stimuli like initial contact indentation and vibrations [3]. The Pacinian and Meissner's corpuscles fall into the RA categories, instead the Ruffini endings and Merkel disks are SA receptors [3].

A further classification is used according to the receptive field and spatial resolution of the mechanoreceptors [4]. Type I are the receptors exhibiting small receptive field (the closest to the skin surface): Meissner's corpuscles (RA I units) and Merkel disk (SA I units).Type II are the receptors characterised by large receptive field (the deepest in the skin) and correspond to Ruffini endings (SA II units) and Pacinian corpuscles (RA II units).

The SA I units (Merkel disk) operate between 2 Hz and 16 Hz, but they are maximally sensitive to very low vibration frequencies ranging from about less than 2 Hz to 3 Hz. They are characterized by high spatial resolution (0.5 mm) and small receptive field (2-3 mm of diameter) [1]. Therefore, these units elaborate the contact information as local pressure and they are sensitive to the local stress strain field. For these reasons, they are suitable to discriminate spatial details, such as points, edges, corners, and curvature [5]. The RA I units (Meissner’s corpuscles) are activated in a range of 3 Hz and 40 Hz and show a uniform and high sensibility along the whole receptive field. Thus, RA I afferents are able to discriminate very fine spatial details concerning the sensation of flutter deformations and vibrations generated by transitory phases of indentation [5]. The RA II units (Pacinian corpuscles) react from 40 Hz to 500 Hz with the highest sensitivity around 300 Hz. RA II units are very sensitive to mechanical transients and vibrations with high frequency content [5]. Finally, the SA II units (Ruffini endings) are excited in a frequency range from 100 Hz to 500Hz. Ruffini endings contribute to the perception of hand configuration and finger position [1].

Receptors	Merkel disk	Meissner's corpuscles	Pacinian corpuscle	Ruffini endings
Adaptation	Slow SA	Rapid RA	Rapid RA	Slow SA
Perceptive field	Small ($11mm^2$) Type I	Small ($9.4\ mm^2$) Type I	Large ($100mm^2$) Type II	Large ($60mm^2$) Type II
Density	70 units per cm^2	140 units per cm^2	20 units per cm^2	10 units per cm^2
Frequency field	2 – 16 Hz	3 – 40 Hz	40 – 500 Hz	100 – 500 Hz
Perceptions	Static Pressure, detection of object spatial structure and form	Transient pressure indentation, motion, grip control	Vibration sensations	Skin stretch sensation

Table 1: Mechanoreceptors classification and main characteristics.

One of the pioneers of texture perception was David Katz, who first has hypothesized the role of friction-induced vibrations (FIVs) on the texture perception process, through the duplex theory of tactile texture perception **[6]**. Substantially, he introduced the concept that the texture perception of surfaces is a process mediated by two coupled but different senses: "spatial sense" for the discernment of coarse textures and a "vibration sense" for an appreciation of finer textures.

Further studies provided by Lederman and Taylor **[7] [8] [9]**and by Hollins **[10] [11] [12]** confirmed the duplex theory of tactile texture perception. Lederman and Taylor, stimulating the fingerprint with roughness of milled gratings, showed that the perception is more related to the spatial properties rather than the vibrational signal. Moreover, the sliding speed has a limited effect on the sensation of roughness, as well as the adaptation of mechanoreceptors does not reduce the perceived roughness. Even if the results apparently refute the duplex theory, they actually confirm it. Indeed, the spatial period of the sample textures used in this study **[8] [11]** was equal to 0.63 mm, which was later found to fall in the case of coarse textures. Hollins' works, comparing psychophysical responses when abrasive surfaces moved across the skin with those obtained during static touch, highlighted few fundamental findings: while fine textures are well discriminated when the exploration procedure is driven by an active contact, they become indistinguishable when only static exploration was achieved.

The role of friction-induced vibrations has then been recently investigated **[13] [14]**. More in general, the understanding of the signals at the origin of tactile perception **[14] [15] [16]** is at the basis of the development of artificial fingers **[17] [18] [19] [20] [21]** and tactile devices **[22] [23]**, with the aim of measuring, evaluating and reproducing touch. Recent studies **[24] [13] [16] [14] [25] [26]** introduce the fingerprint wavelength as an additional parameter playing a role to discriminate fine and coarse textures.

These works highlighted the effect of fingerprint on the frequency distribution of the vibration spectra generated by the finger/texture sliding contact. When the sample roughness wavelength is smaller than the fingerprint one, the main frequency peak depends on the sample roughness. When the sample roughness wavelength is larger than that of fingerprint, the main frequency peak is function of fingerprint wavelength. When the sample roughness wavelength is comparable with respect to the fingerprint wavelength, the spectrum is a function of both of them. In **[27]**, it is shown that the ability to discriminate textures can be related to the acceleration root mean square (RMS) value of the FIVs. On the one hand, surfaces characterized by the closest values of acceleration root mean, turn out to be not easily discriminated. On the contrary, surfaces with substantial different acceleration RMS values are well-distinguished. The role of FIVs on the perception of surface topography has been then investigated on different patterns with either periodical or isotropic topography **[27]** highlighting the direct correlation between vibrational signals and perceived roughness.

The present work addresses a contribution towards a deeper understanding of the tactile perception mechanisms. In particular, investigations are conducted to relate FIVs features and the hedonistic feedback stemming from a panel of individuals. Starting from well-defined surface samples, the sensory campaigns on both perceptual dimension categories and hedonistic feedback have been here related to both the topographical features and the tribological/dynamical signals measured during the act of touch. The aim is to correlate perceived features and hedonistic feedback with objective indexes from the analysis of friction induced vibrations, which mediate the geometrical surface attributes.

2. Materials and methods

2.1 Contact pair topography

- *Surface Samples*

The samples are made of polyurethane resin and obtained by moulding-replication of silicon wafers, primarily engraved thanks to photolithographic techniques performed in clean room. They exhibit a periodic surface topography consisting of a sequence of raised cylindrical "dots", arranged according to a hexagonal network onto a rectangular plate of dimensions 25 × 60 mm (Figure 1). The topographical properties are defined through three parameters: height of dots (H), diameter of dots (D) and the inter-dots distance (or spatial period Sp). The periodicity of the samples are expressed by the equivalent wavelength λ, which is the summation of the dot diameter D and the inter-dots distance Sp. Table 2 reports the characteristic dimensions of the 12 samples tested within both the sensory and the tribo-tactile analyses.

In fact, because of the extent of the tribo-tactile analysis, a reduced subset of 12 samples (Table 2) has been selected, within the larger set (52) of developed samples that have been used for both the sensory analyses and reported in section 3 (See Figure 3). Then, while the whole set of sample is used for the sensory analyses, the correlation with the measured mechanical stimuli is investigated for the selected subset of samples.

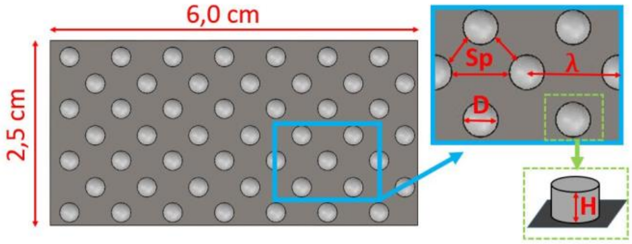

Figure 1: Scheme of samples topography with the respective topographical parameters.

Samples	Height H [µm]	Diameter D [µm]	Spatial period Sp [µm]	Equivalent Wavelength λ [µm]	Perceptual category	Hedonistic perception	
01	27	107	13	120	Smooth	I like a lot	Uniform assessment (votes > 50% for one hedonistic categorization)
02	24	107	53	160	Smooth	I like a lot	
03	19	22	28	50	Smooth	I like a lot	
04	38	108	111	218	Textured	I like	
05	55	208	109	317	Textured	I like	
06	18	71	113	184	Textured	I do not like	
07	14	207	111	318	Textured	I do not like	
08	18	106	607	716	Rough	I do not like at all	
09	14	207	318	524	Rough		Non-Uniform assessment
10	27	502	114	616	Adhesive		
11	29	797	116	913	Adhesive		
12	15	12	126	138	Textured		

Table 2: Characteristic dimensions of the 12 tested samples and sensitivity test results.

- *Surface fingerprint*

The other body involved in the contact pair is the finger. Since its characteristics have a crucial influence on the fine-coarse texture discrimination *[12] [14]*, it is important to define its topographical properties, as done for the surface samples. The main variable that characterizes the fingerprints in terms of FIVs is the wavelength, which significantly varies between individuals *[28]*. Therefore, the friction tests were performed employing the left hand forefinger of the same subject (man, 25 years old), to keep fixed the contact conditions. The measurement of the fingerprint wavelength was executed in both distal and ulnar directions (which will be respectively addressed as longitudinal and transversal directions, from now on).

The statistical distribution of the wavelength width along the two directions has been calculated through image processing, using Fiji software, from the individual's inked fingerprint collected on a tracing paper. The mean fingerprint wavelength corresponds to the one appearing at the top of the distribution curve. The minimum and maximum wavelengths are respectively the lowest and highest values considered, for a number of apparitions equal to 60 % with respect to the mean wavelength. The obtained results are reported in Table 3.

	λ_{min} (µm)	λ_{mean} (µm)	λ_{max}(µm)
Transversal	361.9	430.3	508.3
Longitudinal	502.4	576	635

Table 3: Wavelength of the fingerprints along the longitudinal and transversal directions.

2.2 Tactile sensory analyses

Two different sensory characterizations of the samples were performed, in order to collect the sample perception by a panel of subjects from both a perceptual and hedonistic point of view *[29]*. During the tests, the assessor could entrust only on tactile sense, since the other senses were inhibited. The testers were free to manipulate and to explore the samples in terms of used finger and sliding direction. Nevertheless, a contact sliding exploration was requested.

- *Perceptual categorization task*

The categorization tests were conducted with a panel of 20 assessors composed by seven women and thirteen men, ranging from 24 to 28 years old. During the test, each assessor was requested to group the samples in various categories according to their perceptual dimension (roughness, slipperiness…etc) and to provide one or more words describing each samples category. In order to obtain the mean perception feel, a statistical analysis was performed using the Ascending Hierarchical Classification method *[30]*. From the perceptual categorization tests four perceptual categories were obtained *[29]*:

i) smooth;
ii) rough;
iii) adhesive;
iv) textured.

The categorization obtained for the 12 tested samples is reported in Table 2.

- *Hedonistic sensory test*

For the hedonistic sensory tests, a panel of 43 subjects participated in the tactile perception tests, composed by 30 men and 13 women, ranging from 10 to 69 years old, but mainly included between 20 and 29 years old (56% of the total individuals).

In this case, the task of the assessors was to categorize the samples according to four different levels of tactile appreciation:

i) I like a lot this surface and I would like to find often this surface on daily objects.

ii) I like this surface and I would like to find sometimes this surface on daily objects.

iii) I do not like this surface and I would avoid this surface on daily objects.

iv) I do not like at all this surface and I would not like to find this surface on daily objects.

The assessment was considered "uniform" when more than 50 % of votes fall in the same hedonistic categorization. The hedonistic test results, reported in *[29]*, are quoted in Table 2. While the samples S23, S15 and S18 were not-uniformly assessed, the other samples obtained a uniform assessment.

2.3 Tribo-tactile analysis

The aim of the tribological tests was the measurement of two main signals raised by the sliding contact between fingerprint and sample surfaces, i.e. the friction coefficient (contact forces) and the FIVs. Due to the non-linear behaviour of the phenomena and the high number of parameters involved, a good control of both the mechanical boundary conditions and the physicochemical properties *[28]* of the contact is needed. A dedicated experimental test bench *[31]* was used to reproduce the touch under controlled contact parameters, in terms of mechanical boundary conditions, while a test protocol allowed to optimize the reproducibility of the contact physicochemistry at the fingertip.

- *TriboTouch set-up*

Figure 2 presents the used device. The surface sample (a), mounted on a rigid steel plate, is guided by a compliant system (b) along a linear horizontal planar motion assigned by a linear voice coil actuator (c), while the finger is maintained fixed (passive touch). The relative motion velocity is controlled through a feedback control system and a TTL linear encoder (d) that, together with the linear voice coil actuator, closes the control velocity loop. A hand-support system allows to regulate and fix the fingertip angle of contact thanks to a bar (e) and, at the same time, it supplies stability in order to have a better control on the normal force applied by the operator. Two tri-axial force transducers (f) are placed below the sample to measure normal and tangential forces (and in order to monitor the normal force), while an accelerometer (g) is attached directly on the fingernail by wax to measure the friction-induced vibrations.

The use of the compliant system and the linear voice coil actuator are crucial to satisfy the measurement requirements, since they allow to perform measurements without introducing parasitic noise coming from other sliding or rolling contacts within the system itself, when controlling the sample motion.

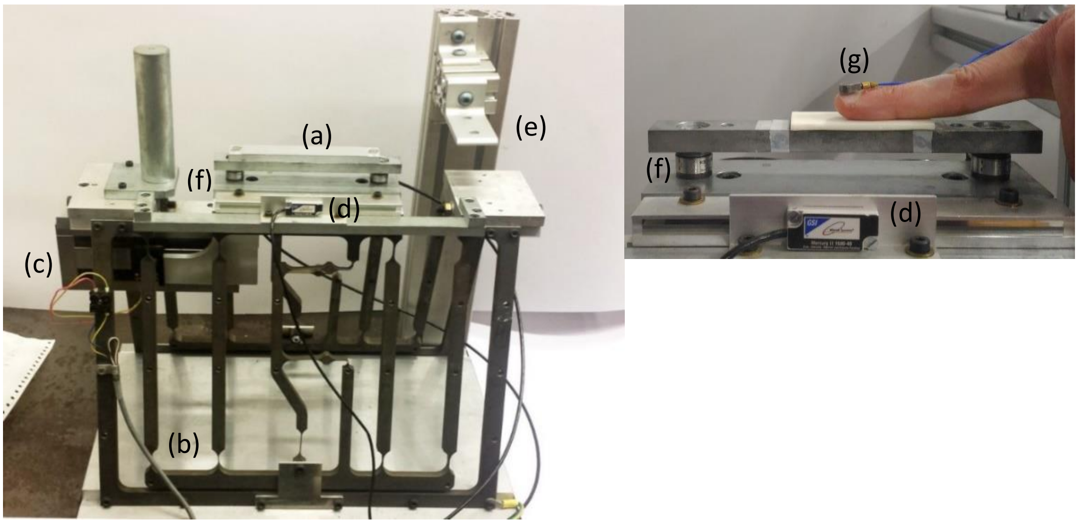

Figure 2: TriboTouch set-up: (a) surface sample, (b) compliant system, (c) linear voice coil actuator, (d) linear encoder, (e) hand support, (f) tri-axial force transducers, (g) light accelerometer.

- *Test protocol*

The measurements were performed by setting, through the TriboTouch set-up, the same contact conditions in terms of sliding speed, angle of contact and normal load for all the tested samples. The values have been chosen according to the commonly used range when a texture exploration occurs *[7] [32]*: sliding speed equal to 30 mm/s, fingertip-sample angle of 15°, and normal contact load equal to 0.4 N. Each sample was tested with the left–hand finger of the operator along the two main sliding directions, i.e. placing the finger along (longitudinal) and orthogonal (transversal) to the scanning direction. Each sample was tested three times for both sliding directions in order to ensure a good reliability of the measurements. Before each test, the samples are ultrasonically cleaned. Moreover, in order to prevent an uncontrollable production of sebum, the fingerprint is cleaned up with common soap, rinsed, and then dry-air dried immediately before performing the measurements. Each test is composed by nine subsequent measurements, and only tests with stable normal contact load, at 0.4 N with a variability in time less than 10%, are retained.

Only the signals acquired during the constant velocity phase (at 30mm/s) are taken into account, and the signals post-processing is performed on Matlab. The friction coefficient, together with the RMS amplitude and spectrum of the induced vibrations are computed and analysed.

3. Sample topography and correlation with sensory analyses

A correlation analysis has been established between the topographical parameters of the samples and the results from the sensory analyses. In particular, it is possible to differentiate the analysis according to the two main physical sample topography characteristics: the physical roughness, i.e. the dot height H, and the physical dot spatial wavelength λ.

For the considered samples, a strong correlation between the physical sample surface features and the perceptual category of the sample was found (Figure 3 (a)).

Looking at the charts, the crucial role of the wavelength, in the discrimination of the perception categories, is highlighted with respect to three λ ranges:

- For small wavelengths ($\lambda < 160$ µm), samples are perceived as smooth.
- Increasing the wavelength (160 µm < λ < 550 µm), both the groups of the textured and rough samples appear.
- Finally, for larger wavelengths ($\lambda > 550$ µm), both rough and adhesive perceived samples are clustered.

Thus, since the wavelength represents the fineness of the texture, according to the Katz's theory *[6]*, the texture perception can be clustered in fine texture perception, medium texture perception and coarse texture perception. In particular from now on, fine textures will be considered when the sample show wavelengths below 160 µm, medium textures when the sample wavelength is in between 160 µm and 550 µm and, finally, coarse textures when the sample wavelength is above 550 µm.

Deeper information are picked up on both the medium and coarse texture perception taking into account the Sp and D values. Dealing with the medium and coarse textures, it is recognised that the inter-dots distance define two different areas of the graph from the perception point of view:

- Below an inter-dots distance Sp of about 300 µm, the samples are perceived as smooth, textured or adhesive, as a function of the dot diameter D.
- Above an inter-dots distance Sp of about 300 µm, the samples are perceived as rough whatever the dot diameter D.

When the Sp value is lower than the threshold one (300 µm), the samples perceived as textured, smooth, and adhesive are clustered with respect to the wavelength value λ.

In particular, it is noticed that the transition between the textured perception and the adhesive one takes place for a wavelength value λ that is close to the spatial resolution of the SAI afferents, i.e. 550 µm.

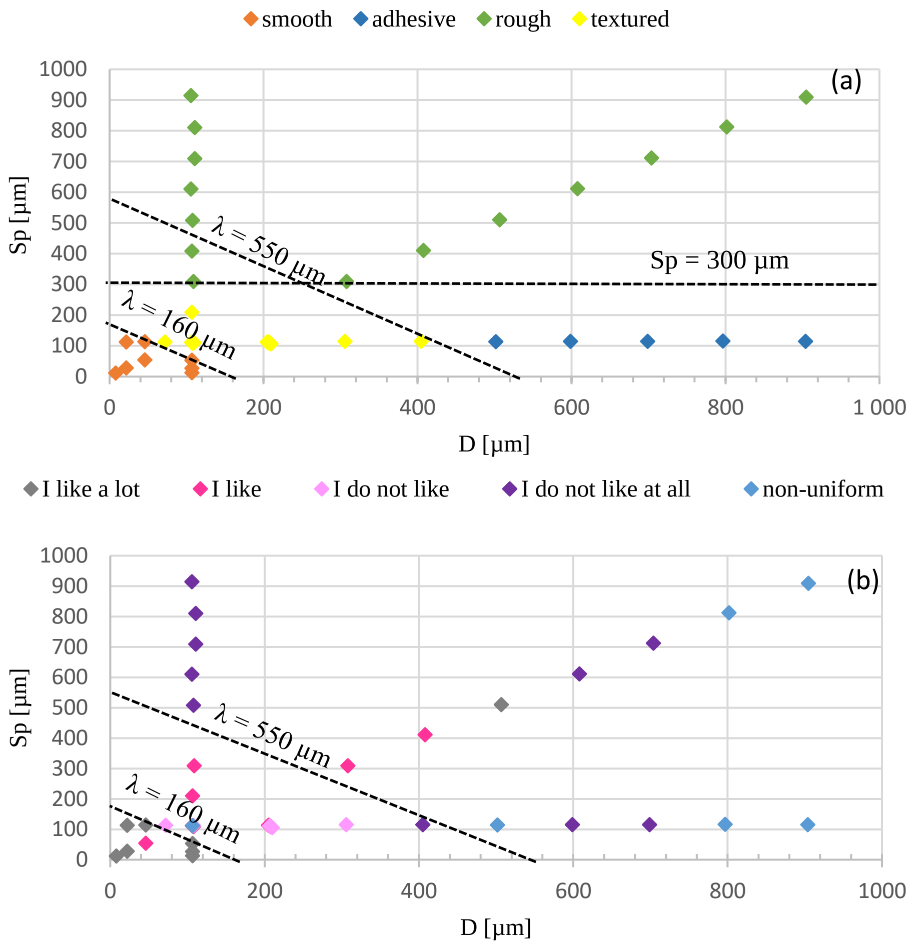

Figure 3: *Samples' perception classes as a function of dots' diameter D and inter-dots distance Sp from a panel of 43 subjects;(a) Perceptual categories,(b) Hedonistic perception.*

These observations, in agreement with previous works *[11]*, suggests that the activation of SA I afferents changes the perception feeling of surfaces. Nevertheless, it does not explain the reason why the surfaces, which belong at the same cluster of physical topography, are perceived in a different manner from a perceptual category point of view. Indeed, considering the coarse textures, a non-unique perception classification of samples is provided, as they are perceived either adhesive or rough. As well, in the case of medium textures, samples are perceived either rough or textured, as a combined function of the topographical parameters. Therefore, a net division of the perception mechanisms as directly function of the topography characteristics of surfaces, considered as fine, medium and coarse textures, seems to be improbable. In other words, the only topography characteristics are not able to directly cluster the

perceptions categories. Conversely, it appears reasonable that the synergy between spatial and vibrational sense is the key to understand the perceptual categories discrimination mechanism.
With respect to the hedonistic sensory analysis, a weak clustering between the different hedonistic classes and the sample geometrical features was found. However, a clear trend as a function of the sample wavelength is identified (Figure 3(b)):

- When the wavelength ranges around the fine texture field, the samples are more appreciated and the judgements are more uniform.
- For medium texture wavelengths, the hedonistic perception is moved towards moderate ratings.
- Finally, the samples characterized by coarse textures, and larger dot diameters, are not appreciated and an increase of non-uniform ratings is obtained too.

Nevertheless, considering the two sensory analyses, a lack of information is highlighted with respect to the origin of such clustering. Notwithstanding, it should be kept in mind that the effective stimuli (mechanical signals) that are transmitted to mechanoreceptor afferents are the static and transient deformation of the skin. The surface topographical properties are thus mediated by these signals to perceive the surface.

4. Mechanical stimuli and tactile perception

4.1 Contact force analysis.

Contact forces and the subsequent friction coefficient represent an important information about a contact pair, in this case the sample surface and the fingertip. In order to evaluate how the friction coefficient affects the surface sample perception, eventual correspondences between perception responses and friction coefficient values were evaluated. Nonetheless, no correlation between the values of the friction coefficient and the sample sensory perception tests was found (Figure 4), neither from perceptual categories nor from hedonistic levels. In Figure 4 no evident clustering or ordering of the categories with respect to friction coefficient can be observed.

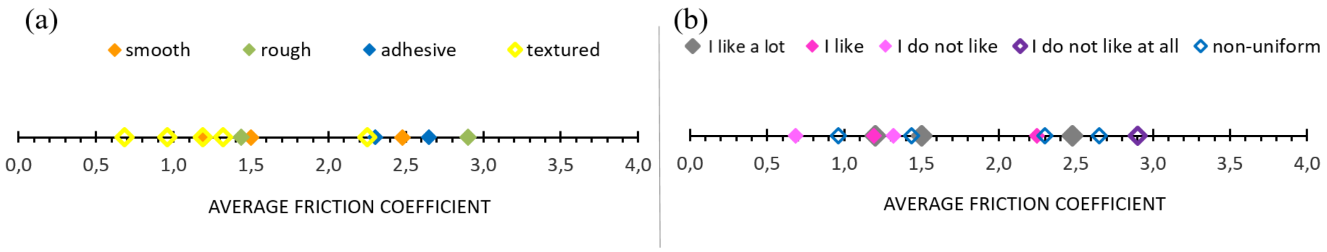

Figure 4: Sample friction coefficient values as a function of the perception vote results: (a) perceptual categories, (b) hedonistic levels.

These results suggest that the friction coefficient does not have a main role in the perception mechanism for the considered samples, at least not in a direct way.

However, it cannot be excluded that the friction coefficient values play a role in favour of the activation and the sensitivity increase of the mechanoreceptors, especially if the SA II are considered *[5]*. Nevertheless, the SA I afferents, which most densely populate the fingertip, are the less dependent on the friction force *[5]*. Thus, it is reasonable to assert that the influence of friction coefficient on the texture perception plays here a marginal role.

4.2 Friction-Induced Vibrations

The FIVs originated by the scanning of the fingerprint on the surface samples were investigated with respect to both the frequency content distribution and the overall amplitude of vibration. In the case of periodic topography, the obtained spectrum of vibrations is characterized by a well-organised frequency content *[14]*. The main part of the signal is concentrated around a well-defined harmonic (which will be called frequency peak in the following), and its super and sub-harmonics. Therefore, the smaller is the value of the fundamental frequency, the closer to each other are the super-harmonics components. Moreover, for smaller fundamental frequencies, a better repartition of the signal energy content, among the fundamental and super harmonic components, has been observed (Figure 5).

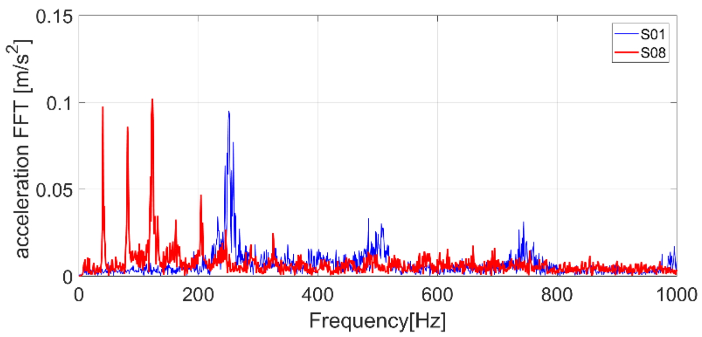

Figure 6: Examples of typical frequency distributions in the case two periodic samples: 01 and 08.

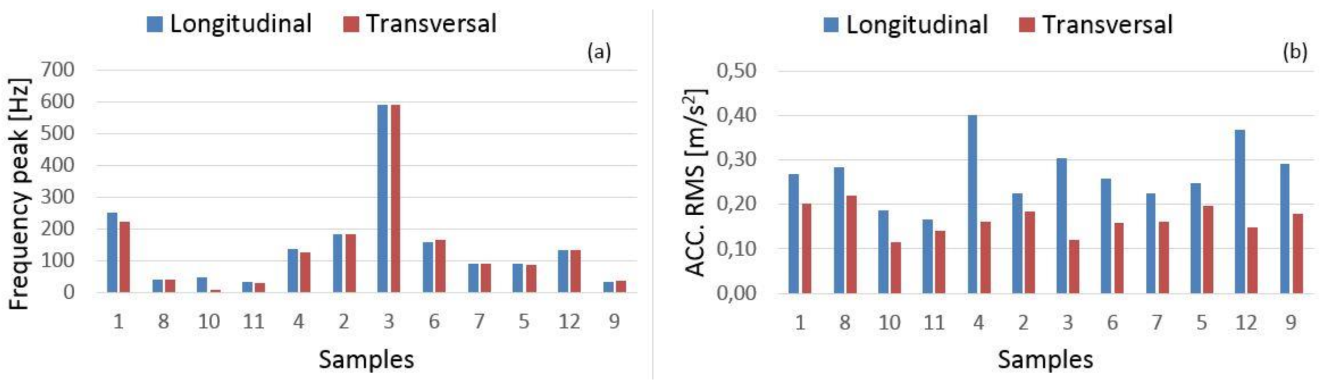

Figure 6: Acceleration vibrational signals measured along longitudinal and transversal sliding directions for each sample: (a) peak frequencies comparison, (b) amplitudes comparison.

The fundamental frequency is used in the following for discriminating the samples using a single parameter, i.e. frequency of the fundamental harmonic. The information carried on by the FIVs are then extracted and discussed considering the amplitude of the vibrations (RMS) and the frequency of the acceleration.

For each sample, since two measurements along the longitudinal and transversal sliding directions were acquired, two sets of vibrational signals were obtained. In order to verify the overall differences along the two directions, Figure 6 shows the signal comparison in terms of amplitude and frequency peak. Comparing the frequency peak values between the longitudinal and transversal sliding directions (Figure 6(a)), negligible differences are observed for the whole samples population. This means that, independently from the sliding direction, the same information about the frequency content of the vibrational signals can be detected by the mechanoreceptors. Considering the amplitude of vibrations (Figure 6 (b)), it is noticed that:

(i) each sample is characterized by higher magnitude of FIVs when the longitudinal sliding direction is achieved, (ii) almost the same trend of variation in amplitude values among the samples is obtained in both longitudinal and transversal sliding directions. Moreover, the differences of the amplitude values, among different samples, are more significant in longitudinal sliding than in the transversal one. From now on, only the measurements of FIVs performed along the longitudinal sliding will be therefore discussed in detail. Notwithstanding, similar considerations can be extended to the transversal direction.

4.3 FIVs and correlation with sensory analyses

In this section, the FIVs information (frequency peak and amplitude of vibrations) are discussed with respect to both results from perceptual categorization and hedonistic levels, in order to highlight possible direct correlations between the vibrational stimuli and the perception mechanism.

4.3.1 Correlation between FIVs and perceptual categories

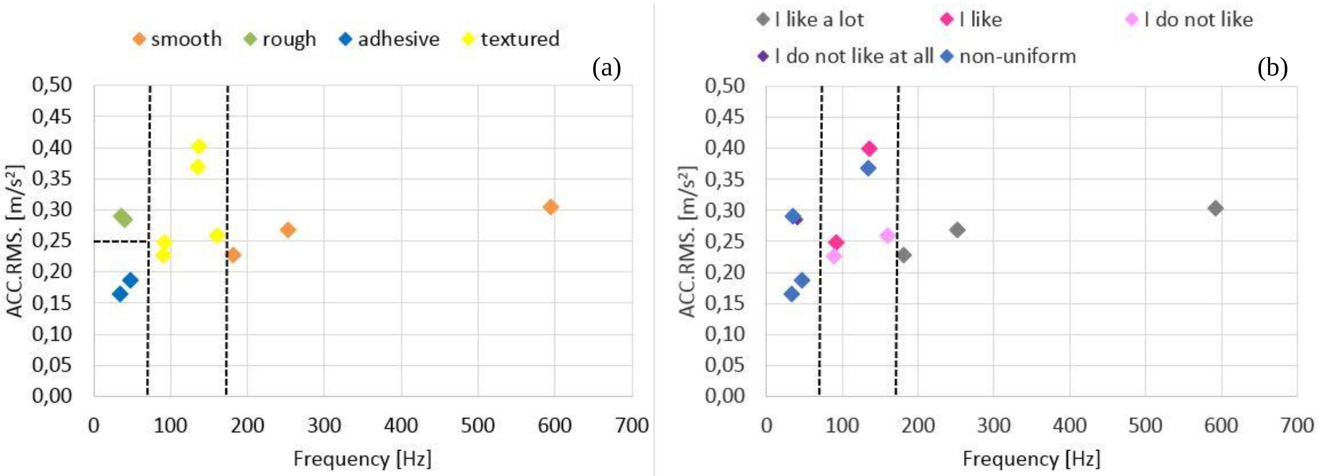

Figure 7 : Perception classes as a function of frequency peak and amplitude of vibrations; (a) perceptual categories, (b) hedonistic perception.

Figure 7 shows the vibrational signal RMS value versus the frequency peak, considering as well the perceptual categories of the samples (dot colours). Looking at the graph, the frequency content of the induced vibrations is able to discriminate the samples in three groups: smooth samples, textured samples and rough-adhesive ones. In particular, the categories are arranged along the frequency axis according to three main zones:

- For low frequency content, ranging from 0 to 60 Hz, the samples are perceived as rough and adhesive.
- Increasing the frequency, the samples are identified as textured (between 60 and 180 Hz).
- Finally, for frequencies above 180 Hz the samples are perceived as smooth.

A direct comparison between the measured frequency spectra of the samples, which belong to each categories of perception, is performed in Figure 8. The frequency spectrum of the samples perceived as rough and adhesive are very similarly shaped and do not show relevant differences in terms of frequency distribution. They show the energy of vibration spread between the few first super and sub-harmonics, in a low frequency range with respect to the most sensitive frequency band of RA II afferents **[1]**. On the contrary, looking at the frequency spectrum of the samples perceived as smooth, a dominant peak, at the fundamental frequency, is observed. For textured surfaces, the main frequency content is close to the most sensitive frequency band of the RA II afferents. In the occurrence of smooth perceived surfaces, the frequency peak falls clearly within the most sensitive frequency range of the RA II afferents.

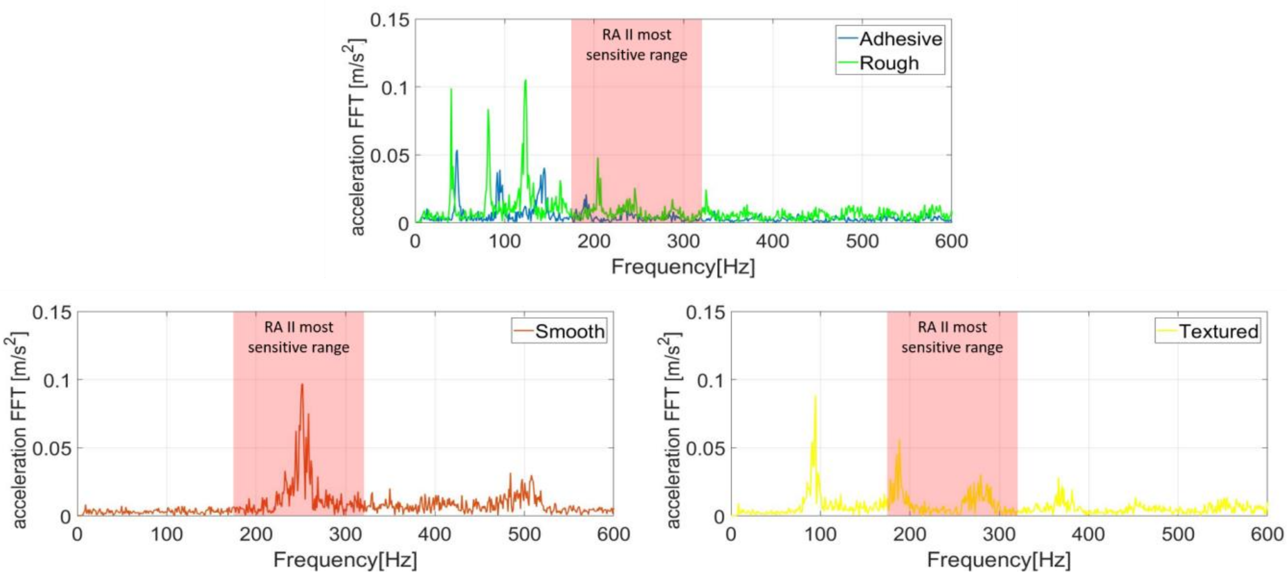

Figure 8: Typical frequency spectrum related to each perceptual categories.

In the case of textured perception, with respect to the smooth one, the typical frequency distribution shows a frequency peak at a lower value of frequency and super harmonics components closer, in amplitude, to the fundamental peak. Therefore, with respect to the RA II afferents, while the sharper peak falls in a lesser sensitive region, only the peaks due to the super harmonics are in the most sensitive region.

Looking at the amplitude of vibrations (Figure 7 (a)), the clustering of the sample in the perception classes appears evident when adhesive and rough samples are compared. Thus, the amplitude of vibrations seems to allow the discrimination of the samples perception when the same information, in terms of frequency peak, is carried by the vibrational signal. Indeed, the rough samples show a higher value of amplitude of vibration, with respect to the samples perceived as adhesive.

4.3.2 FIVs and correlation with hedonistic sensory analysis

Figure 7 (b) shows the hedonistic level as a function of the vibrational signal characteristics (frequency peak and acceleration RMS).

The frequency of vibration, once again, shows a strong correlation with the clustering of the perception classes:

- The hedonistic level "I like a lot" is well clustered, with respect to the others, at higher frequencies.
- Conversely, the hedonistic level "I do not like at all" is situated at lower frequencies.
- The clustering becomes weaker between the "I like" and "I do not like", but they range between the other two extreme hedonistic levels.
- In contrast, samples that are non-unifromly perceived are completely superposed with the samples judged as "I do not like at all" at lower frequencies.
- From the amplitude of the vibrational signals, it is not possible to define a clustering of the hedonistic level. Indeed, all the hedonistic levels are spread along the axis of the amplitude of vibrations and they overlap to each other.

Therefore, moving from samples characterized by higher frequencies towards those with lower frequencies, while the hedonistic level transit from pleasant levels to unpleasant levels, the judgment is passing from a uniform to a non-uniform rating. On the contrary, the amplitude of vibration is not correlated with the hedonistic perception.

4.4 Overall correlation between FIVs, tactile perception and surface topography.

Since in the two sensory analyses the perception classes are driven by the information content carried by the vibrational signals, direct relationships between the FIVs and physical topography should be found out.

Thus, the frequency and the amplitude of vibrations have to decode the geometrical properties of the sample surfaces, from the tactile perception point of view. In the case of samples characterized by periodic texture, it is known that the frequency peak is related to the surface wavelength, through the value of the sliding speed **[14]**. Therefore, once the sliding speed is fixed, the wavelength values consequently cluster the perception classes in line with the frequency peak of the FIVs. Figure 9 shows the relationship between the samples wavelength and frequency of vibrations, as a function of both sensory analyses.

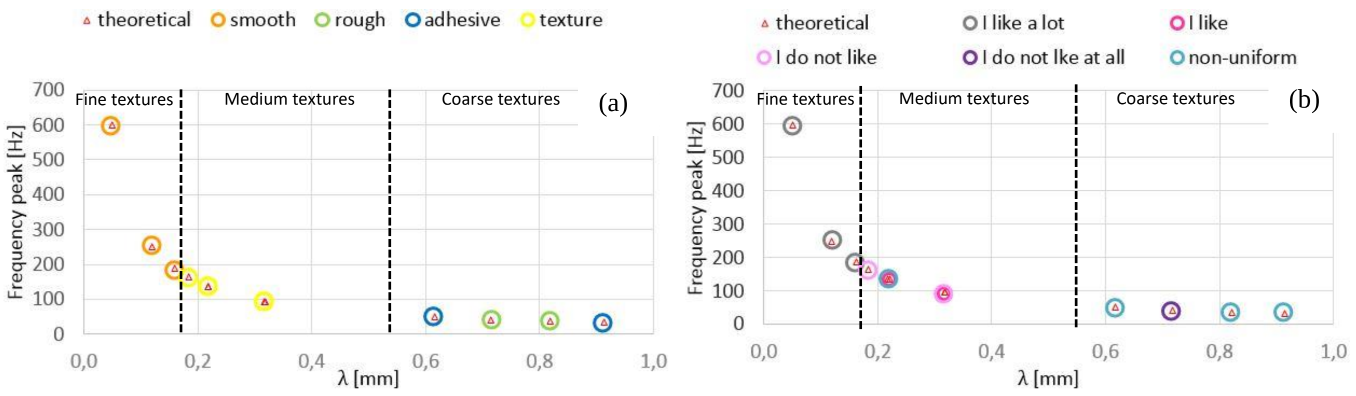

Figure 9: Frequency peak and samples wavelength relationship: (a) perceptual categories, (b) hedonistic levels.

The following information can be extrapolated from Figure 9:

- The frequency peak values are consistent with the wavelength values computed thanks to the sliding velocity and the topographic properties of the samples.
- Looking at the overall behaviour, the three main areas characterised by the different frequency content are once again highlighted: the coarse textures, the medium textures, and the fine textures.

Medium and fine textures

In the medium and fine texture range (wavelength values below 0.55 mm), the frequency peak information is moving along the "knee" of the plots displayed in Figure 9, at low λ values. Thus, small variations of surface wavelength are coded by the vibrational signal, thanks to large variations in frequency. In addition, the frequency values fall in the most sensitive frequency band of the RA II afferents (around 300 Hz), especially in the case of fine texture samples. Indeed, as supposed in the section 4.3, the discrimination task of perception is completely fulfilled by the frequency content of the vibrational signals.

Moreover, it is observed that the transition between fine textures and medium textures occurs almost in the middle of the above-mentioned "knee" of the curve. In other words, when the relevant change in the slope of the curve appears, the transition between fine and medium textures occurs. While the fine texture samples rely on the sharper slope, the sample with medium texture are related to the lower slope zone. Consequently, considering small differences of surface topography, the frequency content of the samples owed to fine textures changes more than with medium textures.

Thus, different samples in the medium texture range are less easily discriminated than the samples belonging at the fine texture range, from the frequency content point of view. Consequently, for the hedonistic perception levels, the non-uniform judgments start to appear in the medium texture field.

Coarse textures

In the coarse texture range (wavelength values above 0.55 mm), a flattening of the frequency of the induced vibrations is shown (Figure 9). Thus, the vibrational signals result to be undistinguished by the frequency point of view. In addition, the frequency of vibration moves away from the most sensitive area of RA II receptors.

Indeed, this case corresponds to the range in which the frequency content of the vibrational signal is not useful to discriminate the different classes of perceptions. However, it has been shown that, for low frequency peak signals, the vibrational signal can discriminate different perceptual categories thanks to the amplitude of vibrations (see section 4.3). In addition, the sample wavelength starts to fall in the resolution region of activation of the SA I afferents (≅0.5 mm), which will add the spatial sense information.

Figure 10 is a plot of the vibrational amplitude against the sample wavelength. A slight decrease of the vibration amplitude is observed, passing from finer textures to the coarser ones. In fact, once that the sliding speed is fixed, the higher the wavelength of the sample is, the lower number of impacts per second between the fingerprint and sample crests occurs. Thus, higher vibrational energy is generated by the contact interface for smaller wavelengths.

Moreover, for the same characteristic wavelength, when the Sp values reach values larger than the half of the fingerprint wavelength (λmean = 0.57 mm), the amplitude of the FIVs increases.

In fact, an increasing of the inter-dots distance Sp above the half crest width of the fingerprint will bring the whole fingerprint crest inside the space between two contiguous dots, increasing the skin deformation. Consequently, higher excitation of the skin is reached.

Indeed, the samples perceived as rough (higher FIVs amplitude) are characterized by inter-dots distance exceeding 0.3 mm, compared to the samples perceived as adhesive (lower FIVs amplitude).

Such assumptions would also explain the increasing of non-uniform assertions when coarse textures are considered. Considering a single surface, the fingerprint topographic features directly determine the FIVs amplitude and then the perceived roughness. Because of the fingerprint topographic dissimilarity between individuals (especially in the case of different gender **[33] [34]**), the amplitude of the FIVs will differ and as well as the amplification of the perceived roughness. Therefore, the uncertainty in the perceived roughness could bring to different hedonistic perceptions, according to the fingerprint features of the assessors. The tests has been performed here with a constant value of the velocity between fingerprint and surface, selected to be representative of the finger kinematics when scanning a surface. The effect of the velocity on FIV spectra are reported in **[14] [27]**.

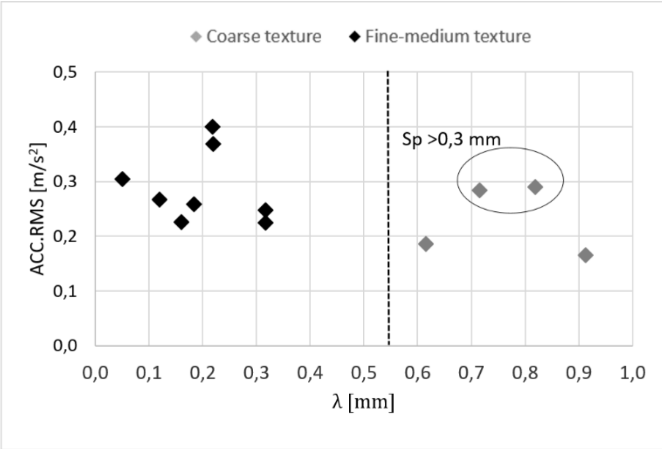

Figure 10: RMS value of friction induced vibrations amplitude as a function of samples wavelength λ.

5 Conclusion

The aim of this work is a step forward on the comprehension of tactile perception and the research of objective indexes able to define the relationship between surface topography, their codification in terms of mechanical stimuli, and finally, the subjective perceptive point of view.

The analysis of the mechanical stimuli, which are the direct elements of activation of the human receptors, is performed, in order to understand how the surface topography information are coded in terms of perceived features.

This has been possible thanks to the design and tribological testing of periodic surfaces, and two different sensory analyses, i.e. the perceptual categorization and the hedonistic perception of these surfaces.

The tested surfaces resulted to be well clustered as a function of the sample topography, according to both hedonistic and categorization ratings:

- When the wavelength ranges within the fine texture field ($\lambda < 160$ μm) the samples are perceived as smooth and uniformly more appreciated in terms of hedonistic feelings.
- For the medium texture wavelength area (160 μm $< \lambda <$ 550 μm), the samples are perceived as textured and the hedonistic perception is moved towards moderate ratings.
- The samples characterized by coarse textures ($\lambda > 550$ μm) are perceived as rough or adhesive. For value of Sp higher than 300 µm the rough perception appears, while Sp value smaller than 300 µm leads to surfaces perceived as adhesive. From the hedonistic point of view, the surfaces are not appreciated and an increase of non-uniform ratings is observed.

However, the perceived geometrical features of surfaces are not linked directly with the perception but they are mediated by the mechanical stimuli, which effectively activate the tactile afferents. The analysis of contact forces and FIVs, and their correlation with the perception analyses, gave the following outcomes:

- The friction coefficient does not affect the texture perception for the tested samples. However, it cannot be excluded that the friction coefficient plays a role in favouring the activation of the mechanoreceptors.
- The FIVs analysis has provided a well-defined clustering of the perception classes, for both sensory tests, according to the frequency content and the amplitude of the vibrational signals.
- The relationships between the FIV features and the surface topography characteristics allow to explain the clustering of the surfaces from a perceptual point of view as a function of topographical features.

Considering the information carried on by the FIVs, the texture perception process has highlighted the following results:

- When the FIVs are characterised by low frequency content, the samples are perceived as rough and adhesive, while the most part of judgments are non-uniform and unpleasant.
- When increasing the frequency of the induced vibrations, textured surfaces are perceived and medium hedonistic judgments are encountered.
- When the FIVs main frequency content is above 180 Hz, the samples are perceived as smooth, and they evoke pleasant hedonistic judgments.
- For coarse textures, the amplitude of FIVs shows correlation with the categorization task. Samples are perceived as rough when the FIVs show higher amplitudes with respect to those resulting from the samples perceived as adhesive.
- The coarser textures seems to imply a coupled mechanism of perception between spatial sense and vibrational sense. The hypothesis is that the amplitude of vibration works as an amplifier of the perceived roughness; the higher is the amplitude of vibrations, the rougher is perceived the sample.
- Finally, the variations in the amplitude of FIVs, as a function of the fingertip topography, could explain the non-uniformity of the rating when coarse texture samples are explored.

Finally, psycho-physical tests showed a strong correlation with the amplitude and frequency of the vibrations induced by the contact between the fingertip and the touched surfaces, which clearly contribute to both the perceptual dimension categorization and hedonistic perception.

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