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Research report

Tactile roughness discrimination of the finger pad relies primarily on vibration sensitive afferents not necessarily located in the hand

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ABSTRACT

This study aims to investigate the relative contribution of remote mechanoreceptors to perception of roughness and spatial acuity. We examined two unilateral pathological conditions affecting differently innervation of the index finger: unilateral carpal tunnel syndrome ($n = 12$) and surgically repaired complete traumatic median nerve section at the wrist following surgical repair ($n = 4$). We employed a control condition consisting of ring-block anesthesia of the entire index in 10 healthy subjects to model pathological denervation of the fingertip. Spatial acuity and the ability to discern roughness were assessed using a grating orientation task and a roughness discrimination task, respectively.

In patients with carpal tunnel syndrome, we observed a significant reduction of spatial resolution acuity but an intact ability to discriminate roughness with the fingertip.

For patients with traumatic median nerve section there was no recovery with the grating orientation task up to 20 months post surgery but a progressive and full recovery with the roughness discrimination task between 6 and 9 months. Finally, in the anesthetic ring bloc group, the nerve block completely disrupted performances in grating orientation task, but unexpectedly left unaffected performances in the roughness discrimination task.

Taken together, these lines of evidence support the view that the neural mechanisms underlying tactile roughness discrimination differ from those involved in spatial resolution acuity. Vibrotaction is necessary and sufficient for the perception of fine textures and, when the innervation of the fingerpad is compromised, information about textures can be captured and encoded by remote mechanoreceptors located in more proximal tissues where the innervation is intact.

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1. Introduction

In a recent paper [32], we showed that there was no significant within-subjects relationship between tactile spatial resolution threshold and tactile roughness discrimination threshold and inferred that the two tactile sub modalities rely on different neural mechanisms, with grating resolution threshold seeming to depend on the spatial structure of afferent signals and roughness discrimination seeming to rely more on intensity coding. Tactile spatial resolution threshold is critically dependent upon tactile innervation for resolution of spatial details needed to make judgments concerning groove orientation, whereas tactile roughness discrimination threshold requires only minimal peripheral innervation to support perceptual decision-making.

Psychophysical and neurophysiologic studies have demonstrated spatial resolution acuity in glabrous skin to be closely related to the density of Merkel neurite complexes associated with slowly adapting type 1 (SA1) fibers [13,26,37,43]. Several investigators have proposed that this SA1 mechanosensitive afferent system may also be involved in the tactual perception of texture roughness [25,37,43]. Yoshioka et al. [43] postulated that spatial variation in SA1 firing rates was the only neural code that could account for the perceived roughness of surfaces with finely and coarsely spaced elements. With an elegant series of experiments, Hollins et al. [15,17] revived interest in Katz's theory [29] arguing that tactile perception of coarse textures depends on a "spatial sense" while tactile perception of finer textures depends on a "vibration sense". They formulated a duplex theory of roughness wherein roughness is thought to be mediated by two neural codes. Accordingly to their theory, coarse textures (with spatial periods $\geq 200 \mu\text{m}$) are encoded by SA1 mechanoreceptors while tactile perception of finer textures are encoded by Pacinian (FAII) and Meissner (FAI) corpuscles responding to cutaneous vibrations generated by the scanning of textures with the fingertips [5,6,14,16,23,43]. However, the thesis asserted by Hollins and Risner [15] was strongly refuted by

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Yoshioka et al. [43] as they postulated that spatial variation in SA1 firing rates was the only neural code that could account for the perceived roughness of surfaces with finely and coarsely spaced.

The aforementioned studies were performed employing direct touching of textured surfaces with the fingertips. However, Klatzky et al. demonstrated that it is possible to perceive texture roughness by indirect touch through a rigid probe [30,31]. Although, several investigators have reported subtle differences between direct and indirect touch [14,18,42], studies employing indirect touch paradigms have underscored the importance of vibrotactile coding in tactile perception of roughness.

The Pacinian and Meissner corpuscles are generally thought to be the primary receptors mediating detection of cutaneous vibrations. The Meissner corpuscles are distinguished from the Pacinian corpuscles by their much smaller receptive field and by being most sensitive to vibratory stimuli in the range from 40 Hz to 60 Hz. The Pacinians are most sensitive in the range from 60 Hz to 400 Hz; they are orders of magnitude more sensitive and because of their sensitivity, their receptive field areas are orders of magnitude larger [5,6,14,23,24,43]. Pacinian corpuscles are abundant in the dermis and subcutaneous tissue beneath the glabrous skin of the hands, in the aponeuroses and tendon sheaths of skeletal muscle, around ligaments, in fascial planes, in the periosteum and interosseous membranes, and in muscle tissue itself [35]. Moreover, multiple lines of evidence have shown that high frequency vibratory disturbances are transmitted readily through cutaneous and subcutaneous tissues, including results of analysis of the visco-elastic properties of these tissues [33] and the common observation in electrophysiological experiments that the Pacinian channel can be activated by transient mechanical disturbances, often quite remote from the receptor location [39]. Furthermore, Morley et al. [34] observed that following a lesion of the lateral digital nerve innervating the terminal phalanx of the left index finger, a patient was able to detect vibration across a wide range of frequencies, reflecting the spread of the vibratory stimulus through the skin and the spatial characteristics of functionally intact receptor/afferent groups innervating neighboring skin [27].

Given that, by their very nature, vibrations generated at the interface of textured surfaces with the fingertip propagate proximally through the finger towards the hand and forearm, and since all these tissues contain highly mechanosensitive receptor afferents able to encode vibrations, we were prompted to investigate the relative contribution of the remote mechanoreceptor afferents to tactual perception of roughness and spatial acuity. Thus, we examined two unilateral pathological conditions affecting differently innervation of the index finger: unilateral carpal tunnel syndrome and surgically repaired complete traumatic median nerve section. Electrodiagnostic studies performed to follow the recovery of the patients suffering from traumatic median nerve section are described in the supplemental text and the associated data are presented in Table S1. And we employed a control condition consisting of ring-block anesthesia of the entire index finger in healthy subjects to model pathological denervation of the fingertip. Spatial acuity and the ability to discern tactual roughness were assessed using a grating orientation task and a tactile roughness discrimination task, respectively, as illustrated in Fig. 1.

2. Materials and methods

2.1. Subjects

Written informed consent forms were obtained from all participants. The Ethics Committee of the Université catholique de Louvain ("Commission d'éthique biomédicale hospitalo-facultaire") approved all of the experimental procedures. All participants were tested using two sensory assessments, as described below.

Three groups of participants took part in the present study. The first group, termed CTS, consisted of 12 patients (6 males, 6 females; 66 ± 14 years of age) who were suffering from unilateral CTS, recruited consecutively at the Hand Surgery Unit

of our institution (Cliniques universitaires St. Luc, Brussels, Belgium). To be eligible, the patients had to fulfill the diagnostic criteria for CTS according to the American Academy of Neurology [36]. These criteria are pain, paresthesia, swelling, clumsiness or weakness of the hand, sensory deficits in the median innervated region of the hand, hypotrophy or motor deficit of the median innervated thenar muscle, and positive Phalen test result (considered to be positive when a 1-min passive forced flexion of the wrist elicits symptoms). A detailed clinical history, a careful clinical examination and an extended neurophysiologic evaluation (electromyographic, nerve conduction velocity, and compound action potential recordings) were performed to exclude the presence of other diseases. Only patients with CTS without etiologic factors [12] were included in this study.

The second group, termed TRA-SEC, consisted of 4 patients (3 males, 1 female; 53 ± 17 years of age) suffering from a complete traumatic median nerve section at the wrist. These patients were treated by a microsurgical suture of the nerve lesion. Due to the anatomical position of the median nerve, all patients presented also a section of the wrist and finger flexor tendons. The tendons were sutured concomitantly with the median nerve. The procedure was performed in the Hand Surgery Unit of our institution by O.B. The patients were evaluated 1 week, 3 months, between 6 and 9 months, and ≥ 1.5 years after their operations. Electrodiagnostic studies were also performed at month 6 and between months 15 and 20 after post-injury. The findings of those electrodiagnostic studies are described in the supplemental text and Table S1.

The third group, termed AN-BLOC, consisted of 10 healthy volunteer subjects (10 males, 31 ± 11 years of age). All of them were free from diseases and injuries that could have affected the tactile sensitivity of their hands. The digital nerves at the base of the index finger were blocked by four injections of 2% xylocaine (Astra-Zeneca®) to achieve a ring-block anesthesia of the entire index finger [1]. Clinical anesthesia was obtained when all sensations were abolished as indicated by complete insensitivity to skin contact with the Semmes Weinstein monofilaments (Lafayette Instrument) [2–4].

2.2. Grating orientation task

The grating orientation task was carried out using JVP Domes (JVP Domes, Stoeltz Co., Wood Dale, IL) on the index finger of the affected hand. The test kit included a serial set of eleven hemispherical plastic dome gratings having equidistant bar and groove widths at the following widths (in mm): 0.35, 0.50, 0.75, 1.00, 1.20, 1.50, 2.00, 3.00, 3.50, 4.00, and 4.50. Each dome was applied perpendicularly to the skin for approximately 2 s with a skin indentation of 1–2 mm (Fig. 1A). The domes were randomly aligned in one of the two orthogonal directions (i.e., with the grooves parallel or transverse to the long axis of the index finger). Blindfolded subjects were required to identify the stimulus orientation before the stimulus was removed. A procedure adapted from that of Van Boven and Johnson was used [7,40]. The 3-mm grating was first applied for 10 consecutive trials using a randomized orientation of the bars. If the subject succeeded with the 3-mm grating, then the next smaller grating (2 mm) was applied and so forth. The test was stopped when the probability of correct answers for the grating reached 50%. If the subject failed at the 3-mm grating, the next larger grating (3.5 mm) was applied. The test pursued with larger gratings until the subject reached a score higher than 75% of correct answers. A simple linear interpolation estimate of the 75% correct grating width was taken as the tactile spatial resolution threshold value. A lower tactile acuity grating score (TAG score) signified better tactile spatial resolution acuity.

$$\text{TAG score} = g_{\text{below}} + \frac{0.75 - p_{\text{below}}}{p_{\text{above}} - p_{\text{below}}} (g_{\text{above}} - g_{\text{below}})$$

where g = grating width of a probe, p = probability of correct answers, *above* = the grating width that results in a score closest to but above 75% correct, and *below* = the grating width that results in a score closest to but below 75% correct.

2.3. Tactile roughness discrimination task

The tactile roughness discrimination task has been explained in detail elsewhere [32]. Briefly, each subject was comfortably seated at a table facing the experimenter and was requested to position the index finger of the dominant hand just in front of two textured surfaces, each with an area of $7.5 \text{ cm} \times 3.0 \text{ cm}$ (Fig. 1B). A cardboard screen was placed over the participant's wrist to block visibility of his or her hand. Without further instructions, the participant was asked to slide the fingertip of their index finger on the first stimulus (located on the left side) and then subsequently on the second stimulus (located on the right side). After each trial, the participant was asked to discriminate the textures by reporting which was the rougher surface. Between trials, the subject raised his or her index finger to allow the experimenter to reposition it on the left side for the presentation of the next stimulus. The subjects scanned each stimulus with a single sweep using their naturally applied contact force and scanning velocity. The subjects wore sound attenuating headphones to muffle any extraneous noise.

Thirteen pieces of sandpaper (see Table 1), with average grit sizes varying from $18 \mu\text{m}$ (grit number P1000, the finest stimulus) to $195 \mu\text{m}$ (grit number P80, the coarsest stimulus) were used as stimuli. Grit number and particle size ("micron grade") are described in accordance with the Federation of European Producers of Abrasive Products (FEPA) P-grading system.

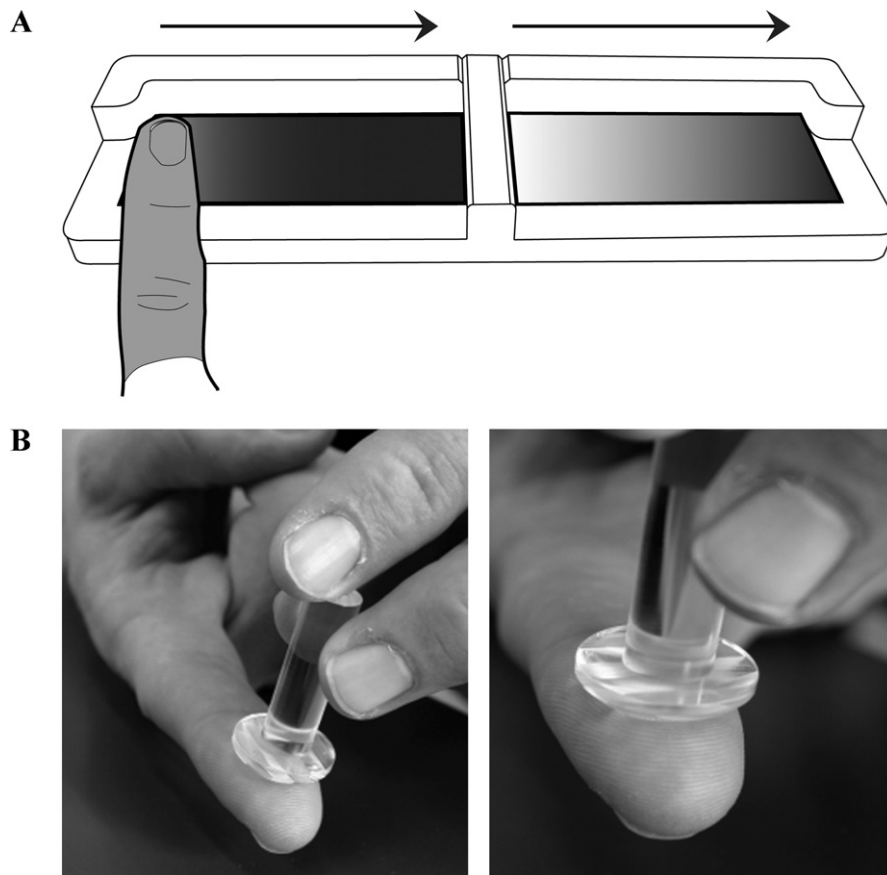


Fig. 1. Sensory assessments. (A) Photographs of a grating orientation task stimulus in use. (B) Illustration of tactile roughness discrimination task apparatus in use.

Two tactile roughness discrimination thresholds (one for rough and one for smooth surfaces) were determined using a double interlaced adaptive staircase procedure based on a two-alternative forced choice paradigm. The tactile roughness discrimination threshold was defined as the amount of change required to produce a 75% just noticeable difference (75% JND) in sensation. The stimulus difference was defined as the difference in particle size between a given stimulus and the reference stimulus (P320). If subjects were able to discriminate correctly the smallest difference in particle size (P240 and/or P360 vs. reference P320), their discrimination performance exceeded the limit of resolution of the stimuli. For these subjects, we allowed a threshold value of half the smallest difference in particle size.

2.4. Statistics

Paired *t*-tests were used to compare the thresholds elicited for the unaffected vs. the affected hand of all participants to this study. Non-parametric statistics were applied when normality tests failed or when statistics were performed on ordinal data. The level of significance for the *p* value was set to 0.05.

Table 1
Set of sandpapers used as stimuli in the tactile roughness discrimination task.

Surface	Stimulus N°	FEPA P-grade	Average grit size (μm)	Threshold
Smoothest	13	P1000	18	S6
	12	P800	22	S5
	11	P600	25.8	S4
	10	P500	30	S3
	9	P400	35	S2
	8	P360	40	S1
Reference	7	P320	46	LR
	6	P240	58	R1
	5	P220	65	R2
	4	P180	78	R3
	3	P120	127	R4
	2	P100	156	R5
Roughest	1	P80	195	R6

3. Results

3.1. Spatial acuity performance in the grating orientation task

As shown in Fig. 2A, a significant reduction in tactile spatial resolution ability in the grating orientation task was observed in the affected hand of CTS patients, relative to the unaffected hand, as evidenced by all tactile acuity grading scores of the patients' affected hands being located above the identity line of the equality plots (paired *t*-test, $t = -2.21$; $p < 0.05$). Grating orientation task performance was measured at four different periods in TRA-SEC patients: within the first week (T0), 3 months (T1), 6–9 months (T2), >18 months (T3). The most dramatic finding for the TRA-SEC group was that the patients were unable to perceive grating orientation on the index finger pad of the affected hand for more than 18 months postoperatively. Of note, and as already reported in the literature [8], the reproducibility of the grating orientation task for the unaffected hand was very high across the four time points ($p > 0.5$). The mean tactile acuity grading score was 2.15 mm (± 0.72 mm) in the normal subjects (age 31 ± 11) but after anesthetic block of their fingers, they were all completely unable to perform the task.

3.2. Roughness discrimination performance

In subjects with the carpal tunnel syndrome, there was no difference in roughness discrimination between the affected and non-affected hand for either smooth or rough stimuli (Fig. 2B and C. Wilcoxon's paired ranked test, $p > 0.05$ for both). The TRA-SEC patients' performance data for rough and smooth textures in the tactile roughness discrimination task for the same four postsurgical time periods described above are shown in Fig. 3. During

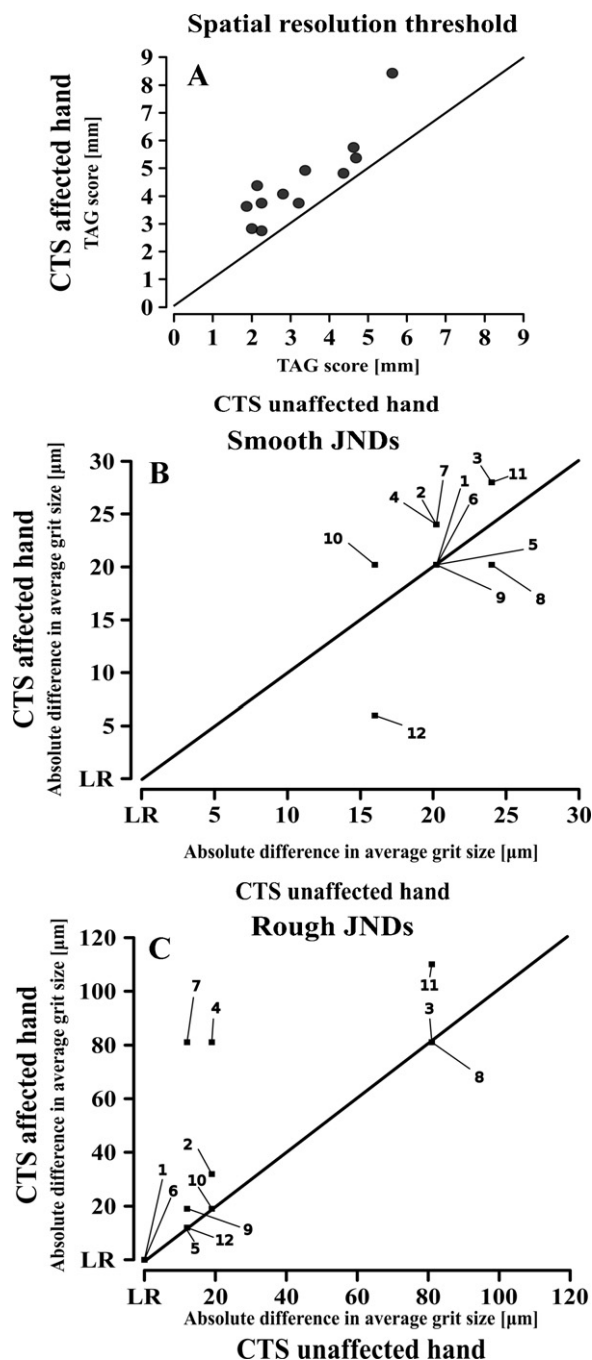


Fig. 2. Patients with unilateral carpal tunnel syndrome (CTS). (A) Tactile spatial resolution thresholds in TAG scores for unaffected vs. affected hands. (B and C) Just noticeable differences (JNDs) in tactile roughness discrimination thresholds with smooth stimuli (B) and rough stimuli (C) in unaffected vs. affected hands. The 75% JNDs are expressed as the absolute difference in the average grit size between a given sandpaper and the reference sandpaper (P320; see Table 1), where LR represents the limit of resolution. The line in each graph represents the “identity line”.

the first week post surgery (T0), all TRA-SEC patients had no ability to perceive roughness when scanning the sandpapers with the index finger pad of the affected hand. Three months after surgery (T1), some patients were able to discriminate a couple of the roughest sandpapers. During the 6–9-month time period (T2), both the smooth and rough tactile roughness discrimination thresholds measured on the index finger pad of the affected hand became similar to those in the unaffected hands. It should be noted that we observed excellent reproducibility of the tactile

roughness discrimination test results across the four different time periods for the index finger pads on the patients' unaffected hands. Finally, as shown in Fig. 4, the anesthetic ring bloc had no effect on smooth or rough tactile roughness discrimination thresholds in the AN-BLOC group (Wilcoxon's paired rank test, $p=0.10$ and $p=0.46$, respectively). In fact, most (8/10) of the AN-BLOC participants reported spontaneously that they could feel vibrations but could not characterize the un/pleasantness of touch sensations while under anesthetic block.

4. Discussion

In the present study, we found that patients with CTS had a significant reduction of spatial resolution acuity while maintaining an intact ability to discriminate roughness with their fingertips. On the contrary, tactile roughness discrimination performance was unaffected by entrapment of the median nerve. The TRA-SEC patients exhibited no performance recovery in the grating orientation task for up to 20 months postoperatively, but did show a progressive and nearly full recovery in their tactile roughness discrimination performance by 6–9 months postoperatively (T3). Finally, in the AN-BLOC subjects, who were given an anesthetic ring bloc in the absence of any pathology, we observed disrupted grating orientation performance in the absence of any apparent effects on their ability to perform the tactile roughness discrimination task.

Taken together our results showed that the neural mechanisms underlying the tactile roughness discrimination differ from those involved in spatial resolution acuity. Remarkably, our findings provide some evidence that roughness discrimination rely primarily on vibration sensitive afferents not necessarily located in the hand. This dissociation raises several questions. Firstly, how are the physical properties of tactile stimuli, produced at the finger pads in contact with the material, conducted to sensory structures remote from the finger pads? Further, where and how is information related texture encoded and conveyed to the central nervous system.

Similar subjective roughness magnitudes are obtained when textured surfaces are actively scanned indirectly with a rigid probe or directly with the finger pad, indicating that vibrations generated at the interface of the probe with textured surfaces carries the critical information needed for roughness discrimination [9,30,31]. Moreover, performance on the tactile roughness discrimination task employed here is independent of variables such as normal force, tangential force, and average scanning velocity [32]. Consequently, we can surmise that the fully anesthetized index finger may act like a probe, transmitting the biophysical interaction of the finger pad with external stimuli to remote tactile sensors that are capable of encoding this information. This line of reasoning can also be applied to explain the dissociated abilities observed in the CTS group. Indeed, the numbness and loss of the sensory nerve responsivity experienced by CTS patients is thought to be due to entrapment of the median nerve in the carpal tunnel leading to pathophysiological changes such as decreased nerve conduction velocity in large myelinated fibers [41]. Presumably, the presently reported grating orientation task performance deficit in CTS patients also reflects these physiopathological changes. The absence of a deficit for the CTS patients in roughness discrimination performance may be analogous to the intact roughness discrimination performance we observed in our control subjects while they had an anesthetic digit bloc. That is, the biophysical information related to material roughness may be transmitted to remote receptors while the anesthetized index finger or the finger of a CTS-affected hand acts as a probe. These observations are concordant with those of Morley et al. [34] who reported an increase in vibratory detection threshold for low frequencies (5–40 Hz) and

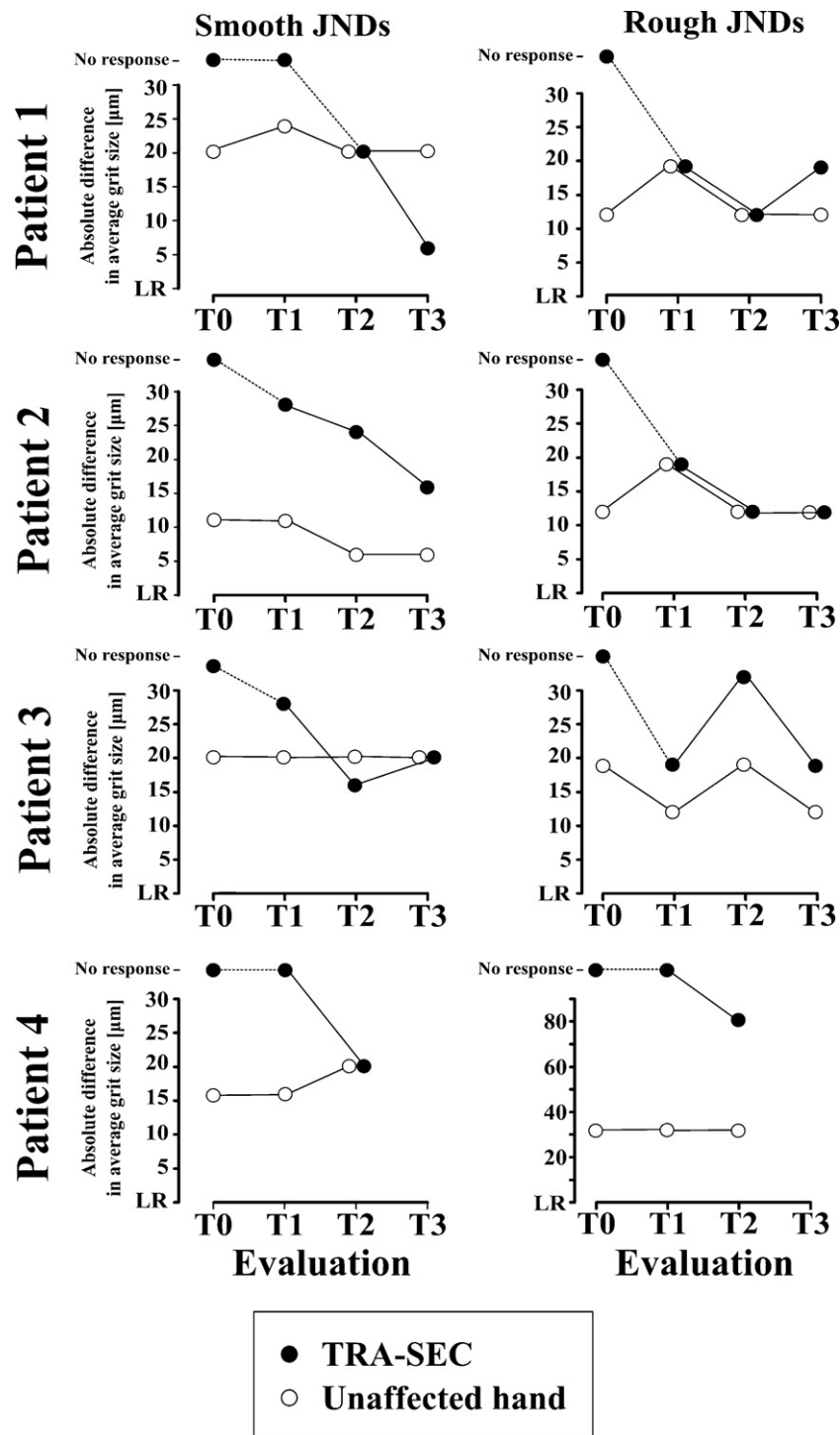


Fig. 3. Patients with a unilateral traumatic sectioning of the median nerve and wrist flexor tendons (TRA-SEC). Just noticeable differences (JNDs) in tactile roughness discrimination thresholds with smooth stimuli (left column) and rough stimuli (right column) in unaffected (open circles) vs. affected (black circles) hands. The 75% JNDs are expressed as the absolute difference in the average grit size between a given sandpaper and the reference sans paper (P320; see Table 1), where LR represents the Limit of Resolution. Patients were evaluated four times (except patient 4 who was evaluated three times) during the post-surgical period, i.e., at 1 week (T0), 3 months (T1), between 6 and 9 months (T2), and ≥ 1.5 years (T3).

unchanged detection of high frequencies (80–250 Hz) following a lesion of the lateral digital nerve innervating the terminal phalanx of the left index finger. In their interpretation of these findings, Morley et al. suggested “the differential effect of the nerve lesion on vibratory thresholds reflects the spread of the vibratory stimulus through the skin and the spatial characteristics of functionally intact receptor/afferent groups innervating neighboring skin”. It is interesting to underline here that the detection of ‘flutter’ elicited

by frequencies between 5 Hz and 40 Hz is mediated by activity in the FA1 units reflecting the importance of these units for extracting spatial features of dynamic mechanical events such as scanning across a textured surface.

The present findings have important implications with respect to where and how the biophysical information concerning textured surfaces is encoded and conveyed to the central nervous system, particularly when sensors in the fingertips are bypassed

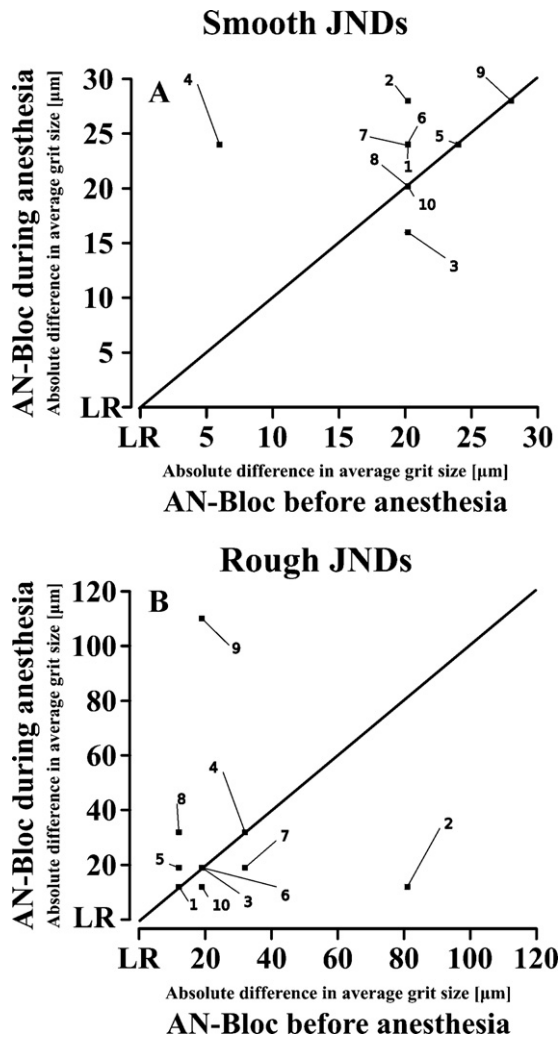


Fig. 4. Subjects with anesthetic ring bloc of the index finger (AN-BLOC). Just noticeable differences (JNDs) in tactile roughness discrimination thresholds with smooth stimuli (A) and rough stimuli (B) before and during anesthesia. The 75% JNDs are expressed as the absolute difference in the average grit size between a given sand-paper and the reference sans paper (P320; see Table 1), where LR represents the limit of resolution. The line in each graph represents the “identity line”.

as a result of a nerve block or peripheral neuropathy. Our results suggest that vibrations travel to remote skin locations where the innervation is intact, and that remote mechanoreceptors (most probably Pacinian afferents) would mediate residual roughness discrimination. Indeed, Delhaye et al. [10] observed that non-periodic vibrations generated at the index fingertip when scanning sand-papers were readily transmitted to the wrist and forearm. The frequency content of the vibration did not enable to discriminate the different stimuli. However, the intensity of the signal was a good candidate to code the roughness of the texture.

As noted in the Introduction, textures with spatial periods greater than $\sim 200 \mu\text{m}$ are encoded by SA1 receptors in the finger pads, whereas roughness discrimination of finer textures (spatial scale $< 200 \mu\text{m}$) is mediated by the encoding of cutaneous vibrations generated during scanning movements. The Pacinian afferents, which are the primary receptors that encode these cutaneous vibrations [5,6,14,23,38,43], are present in the subcutaneous layer of the skin but are also observed near tendons, periarticular, and interosseous ligaments and muscles [35]. It is perhaps worthwhile to recall Hunt et al. [20–22] discovery of very sensitive rapidly-adapting vibration receptors in the interosseous nerve of the hind limb in cats that responds to vibrations transmitted

through the foot pad “almost like a seismograph”. Hunt [19] characterized them as Pacinian corpuscles with a sensitivity so great that very small vibrations transmitted through the skin and soft tissues, even applied at a considerable distance, readily evoked vigorous discharges. Jozsa et al. [28] found that all of the known types of mechanoreceptors were present in the myotendinous junctions of human palmaris longus muscles. Pacinian corpuscles were observed frequently on the tendineal side, but rarely on the muscular side. In turn, Golgi tendon organs were observed frequently on the muscular side, but rarely on the tendineal side. They found that receptors were distributed homogeneously in both the muscle and tendon parts of the junction, with a distance at least $250 \mu\text{m}$ between two mechanoreceptors. Fallon and Macefield [11] showed that the response profile to small vibrations of muscle spindle primary and secondary endings overlapped with that of Golgi tendon organs (20–120 Hz). They further demonstrated that these three receptor types had similar thresholds when stimuli were delivered to the parent muscle’s distal tendon, but only during weak voluntary muscle contraction ($\pm 5\%$ of maximum voluntary contraction). In other words, Golgi tendon organs (1b afferent fibers) located in the distal tendons could potentially participate in the encoding of vibrations generated during active scanning, employing direct (through the fingertip) or indirect (through a rigid probe) touch of textured objects. It is important to recall here that, when the muscles were completely relaxed, Golgi tendon organs did not respond to vibration. Therefore, it should be possible to study the relative contribution of Golgi tendon organs relative to that of Pacinian corpuscles by comparing roughness discrimination task performances in active, passive and pseudo-passive scanning trials of textured surfaces using an anesthetic ring block of the index finger with well-controlled wrist positions and voluntary muscle contractions (e.g., $\pm 5\%$ of maximum voluntary contraction according to Fallon and Macefield’s observations [33]).

Given the aforementioned prior findings, the current results confirm that the neural mechanisms underlying roughness perception for fine textures differ from those involved in spatial resolution acuity [32]. Many previous studies [14,15,17,32,42] have shown that perception of roughness of finer surfaces involves detection of cutaneous vibrations generated when textures move across the skin. When the mechanosensitive afferents from the fingertips are rendered ineffective, such as in our TRA-SEC patients and AN-BLOC subjects, the tactile spatial acuity encoded in the SA1 and FA1 afferents is, as expected, lost completely. However, roughness perception based mainly on vibrations generated at the finger pads is preserved in the absence of functional mechanosensitive afferents in the fingertips since these vibrations are transmitted to remote mechanosensitive transducers located in proximal tissues where the innervation is preserved. During active scanning of textures with the index finger, these remote transducers are sensitive enough to allow normal roughness discrimination ability without any contribution of the mechanoreceptors in the fingertips. Further investigations are needed to evaluate, in normal conditions, the relative contribution of these remote mechanoreceptors to the perception of texture.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.bbr.2012.01.018.

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