

Vibrography: Single-Interval Up/Down (SIUD) Adaptive Vibrotactile Threshold Estimation of the Glabrous Hand and Perioral Face in Neurotypical Adults

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ABSTRACT

Many acquired (cerebrovascular stroke, traumatic brain injury) and progressive neurological conditions (Parkinson's disease, ALS) manifest observable impairments in movement, while changes in somatosensory function may be inconspicuous and more difficult to measure. Research trials and clinical study of movement disorders would benefit from a device and control software that can be used to assess an individual's cutaneous sensitivity to highly controlled mechanical stimulation over a range of test frequencies, similar in concept to pure tone behavioral audiometry. In the present report, we describe the implementation of an automatic single-interval up/down (SIUD) adaptive procedure to estimate vibrotactile detection thresholds (VDT) of the dominant glabrous hand and homolateral perioral skin in response to sinusoidal mechanical stimuli presented at 5, 10, 50, 150, 250, and 300 Hz. The resulting VDT function, herein known as a vibrogram, can be acquired in approximately 3 minutes 45 seconds for any given skin site.

An embedded field programmable gate array (FPGA) microcontroller (cRIO National Instruments) operating under MS Windows 8.1 is used for real-time stimulus generation and randomization of test frequencies, adaptive stimulus amplitude control, threshold response data visualization, and automated logging of the subject's threshold results to an Excel file. This new system was tested on the lower face and glabrous hand in a cohort of 89 neurotypical adults which revealed that VDT's were significantly dependent on stimulus site ($F=248.64$, $p<.0001$), and frequency of vibrotactile stimulation ($F=65.19$, $p<.0001$). Sex of the subject was not a significant factor ($F=0.26$, $p=.612$). The differences in the VDT's between the hand and face are presumed to reflect the unique typing and distribution of mechanoreceptors in the face and hand, and differences in the integument at these two sites. The increased sensitivity (classic U-function) at 250 Hz, attributable to the presence of the rapidly adapting Pacinian corpuscles in the glabrous hand, was not apparent in the perioral vibrogram. The automation of our VDT tracking algorithm, modeled after provides clinical investigators with a reliable tool for rapid assessment of the cutaneous somatosensory system on both glabrous and hairy skin in humans across the lifespan.

Introduction

The face and hand convey our identity, manipulate and interact with the environment, and express emotion and communicative intent. The skin covering these structures with its intricate net of

neurites and mechanosensory endings also serves as a receiver of tactual (haptic) information for detection and recognition of touch, shape, texture, pleasure, consequences of movement, and to alert

us of potential environmental hazards. An intact integumentary system also provides a safe environment for our bodies through a bidirectional barrier accomplished by the epidermis to protect and reproduce our DNA [1]. In many acquired and progressive diseases however, somatosensory impairment often leads to higher mortalities due to limited activity and increased risk of injury. Not only is there a disruption of tactile reception and interpretation, there is often a deficit in coordinated motor performance due to a loss of feedback mechanisms necessary for stereognosis, kinesthesia, and movement related proprioception. An estimated one in two stroke survivors have enough loss of the sense of touch that they have difficulty with everyday activities [2]. Ischemic damage to cortical and subcortical regions in stroke results in degraded motor execution and management of somatosensory signals from peripheral receptors [3,4].

Additionally, there is widespread disruption of excitatory and inhibitory networks responsible for somatosensory, executive and visuospatial processing [5-6]. The resulting impairment can lead to life-long sensory sequelae and contributes to functional deficit and hemispatial neglect [7-9]. In another acquired disorder, traumatic brain injury, elevated intracranial pressure [10,11], and axonal torque injury [12] can lead to long-term somatosensory impairment [13-15]. As with cerebrovascular stroke, the extent of somatosensory deficit can be difficult to identify in many of these patients.

Some neurodegenerative diseases have a negative impact on somatosensation, including Parkinson's disease (PD), in which primary dopaminergic denervation of the basal ganglia is associated with abnormalities in vibrotactile thresholds, object discrimination, and pain sensitivity [16-19]. Parkinson's-related movement 'freezing' may be due to reduced connectivity to Supplementary Motor Area (SMA) and pre-SMA, altering Somatosensory Temporal Discrimination Thresholds (STDT) that affect motor production and timing [20,21]. Moreover, continuous adjustments to dopaminergic treatments and evolving degeneration results in a constant fluctuation of somatosensory symptoms that may require long-term monitoring [22,23].

Like PD, the progression of amyotrophic lateral sclerosis (ALS) may degrade somatosensory integrity. Even though ALS is predominantly characterized by motor neuron degeneration, peripheral and central degeneration of sensory pathways can occur, particularly in early stages of the disease [24-27]. Non-motor progression as evidenced by spinal imaging of the dorsal column [28] and sensory nerve biopsy [29], might be more readily assessed in these patients using non-invasive somatosensory threshold testing in the clinical environment. Arguably even more common in human health issues, changes in peripheral and central vascularization such as those seen in diabetes and heart disease, greatly affect somatosensation and the integrity of the integumentary system [30-33]. As in neurological disease, poor tactile acuity due to problems with periph-

eral circulation should be evaluated over the course of therapeutic intervention and disease progression. Despite the importance of measuring the integrity of somatosensory pathways in damaged systems, the availability of non-invasive, time-efficient assessment methods are limited. In clinical settings it can be difficult to evaluate specific somatosensory impairment or ascertain how much somatosensory damage is contributing to problems with motor performance [34-36].

From a long-term care perspective, rehabilitation research has shown that compromised somatosensory function is related to longer length of stays for institutionalized patients [37,38] and lower quality of life ratings from patients who are living at home [39,40]. Thus, the goal of the present study was to describe our design and implementation of an automatic single-interval up/down (SIUD) adaptive procedure and microprocessor-based hardware control system to estimate vibrotactile detection thresholds (VDT) of the dominant glabrous hand and homolateral perioral skin in response to sinusoidal mechanical stimuli presented at frequencies ranging from 5 to 300 Hz in a cohort of young adults. We hypothesized this automated (3min-45sec) SIUD VDT procedure would reveal significant differences in vibrotactile threshold as a function of site (hand versus face) and stimulus frequency.

Materials and Methods

Participants

Eighty-nine (89) neurotypical adults (59F/30M [24.33 (SD=5.68) years] were recruited regardless of race or ethnicity. Written informed consent, approved by the university Institutional Review Board, was obtained for each participant. Participants were compensated for their participation in this study. Eighty-six adults reported right-hand dominance, and 3 reported left-hand dominance. Inclusion criteria: no report of neurological or psychiatric illness, and not taking regular medication. Exclusion criteria: Neurological, sensory and/or muscular deficits, psychiatric abnormalities, trauma to face and/or hand, or with abnormal skin sensitivity on face or hand.

Vibrotactile Detection Threshold (VDT) Assessment for Hand and Face Stimulus Control

A linear electrodynamic exciter motor (Brüel & Kjaer model 4810 Minishaker, +/- 3mm displacement range) controlled by our software (VIBROS) was used to assess cutaneous vibrotactile sensitivity in the lower face and hand. Adaptive stimulus control was achieved using a National Instruments cRIO real-time FPGA embedded controller programmed in LabVIEW to synthesize (NI 9263, 16-bit, 100KS/s) 1-second sinusoidal bursts followed by an off-state for 1-second. A linear rise-fall decay function of 100 ms during burst generation circumvented mechanical transients associated with the on/off waveform transitions. This voltage signal was conditioned by a Brüel & Kjaer model 2706 power amplifier and input to the motor. The Minishaker includes custom fixtures

and an integral Schaevitz subminiature Differential Variable Reluctance Transformer (DVRT) sensor to transduce displacement for precision vibrotactile stimulation and measurement, a stainless-steel shaft and nylon contactor probe (Area = 0.5 cm²) and a stainless-steel rigid surround (annular gap = 1 mm).



Figure 1: VDT at the glabrous index fingertip.



Figure 2: VDT at the oral angle.

The probe-surround was coupled to a linear micrometer translation stage that was used for actuator displacement calibration and skin contactor preload. This fixture configuration allows the surface of the rigid surround to be adjusted relative to the contactor probe to produce a 500 μ m tissue preload against the moving stimulator probe. The DVRT displacement sensor provided an output signal linearly related to contactor probe displacement from DC to 800 Hz (resolution 0.01 μ m). Participants were seated in a medical-grade hydraulic examination chair with an articulating headrest and a height-adjustable worktable and asked to press a response button as soon as they detected the vibratory stimulus. The Minishaker was coupled to a wall-mounted Zeiss operating microscope arm which provided for stable positioning near the target skin surface (hand or face). The orientation of the motor's

probe-surround to the glabrous finger and oral angle is shown in Figures 1 & 2. A double adhesive collar (7/16" ID) was placed on the stainless-steel surround fixture of the Minishaker to secure placement of the probe on the skin.

Adaptive Vibrotactile Threshold Tracking Algorithm: A single-interval up/down (SIUD) adaptive procedure originally described by Lecluyse and Meddis [41] for assessing auditory function, was incorporated into our somatosensory research to estimate vibrotactile thresholds at 5, 10, 50, 150, 250 and 300 Hz on the glabrous surface of the distal phalanx of the dominant index finger, and at the homolateral nonglabrous surface of the oral angle. These sinusoidal vibrotactile inputs correspond to the frequency sensitivity of cutaneous mechanoreceptors innervating the face and hand. Test order for site and stimulus frequency was randomized among participants. Participants wore circumaural headphones with narrow-band noise plus a continuous pure tone (70 dB SPL) centered at the active test frequency to mask the potential acoustic emittance associated with the Minishaker.

Participants were instructed to press a response button when they perceived 'felt' the vibratory stimulus. We briefly describe our adaptation of the Lecluyse and Meddis algorithm below. The initial stimulus amplitude for any given stimulus frequency was set at a supra-threshold level in order to ensure a detection response. The initial step size was set at 10 dB, and then randomly varied in a \pm 5 dB range relative to the initial amplitude. After the first negative response, the stimulus level was set at the mid-point between the previous 2 levels, and a 2dB step was subsequently utilized. The VDT test procedure continued for 8 trials starting from the trial prior to the first negative response. The algorithm implemented in this study also used false positive detection tests (foils) in which no vibrotactile stimulus was presented to ensure participant vigilance. These false positive trials were implemented in 20% of the successive trials, and on software detection of a false positive trial, it was discarded, and a new trial was initiated. The number of trials (n = 8) included in threshold estimation was chosen in order to attain an accuracy of \pm 2 dB and this number excludes the false positive trials which typically extend any given threshold run by 1 or 2 additional trials [42].

Statistical Analysis

A repeated measures general linear model (GLM) using the factors Stimulus Frequency [6 levels: 5, 10, 50, 150, 250, 300 Hz], Skin Site [2 levels: glabrous index finger distal phalanx, oral angle hairy skin], and Sex [2 levels: Female, Male] was performed using Minitab[®] v17.

Results

Vibrotactile thresholds were obtained for the glabrous skin of the index finger and hairy face in all 89 participants in less than 4 minutes per structure using the SIUD adaptive threshold procedure. The GLM statistical analysis revealed VDT's were significantly dependent on *stimulus site* (F=248.64, p<.0001) and *frequency*

of mechanical stimulation ($F=65.19, p<.0001$). Sex of the subject was not significant ($F=0.26, p=.612$). As shown in Figure 3, VDTs pooled among all subjects revealed that the glabrous finger is most sensitive and shows the classic U-function attributed to the PC-re-

sponse at 250 Hz. The hairy facial skin site at the oral angle lacked the PC-response at 250 Hz. A summary of the GLM ANOVA and the estimated fitted means are given in Tables 1 and 2, respectively.

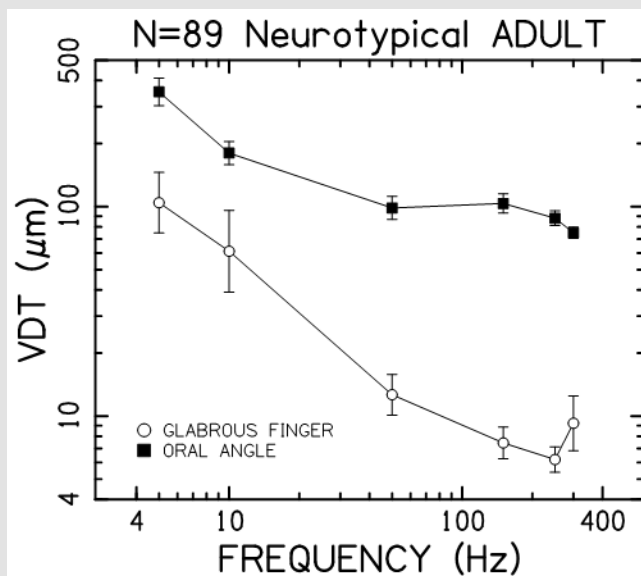


Figure 3: Vibrotactile threshold functions for the glabrous index finger tip, and lateral face at the oral angle (hairy skin) based on 89 neurotypical adults.

Table 1: GLM Analysis.

| Factor Information | | | |
|--------------------------------|-------|--------|--------------------------|
| Factor | Type | Levels | Values |
| Frequency (Hz) | Fixed | 6 | 5, 10, 50, 150, 250, 300 |
| STRUCTURE (Finger, Oral Angle) | Fixed | 2 | 0, 1 |
| SEX | Fixed | 2 | 0, 1 |

| Anova | | | | | | | |
|-------------------|------|---------|--------------|---------|---------|---------|---------|
| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
| FREQUENCY (Hz) | 5 | 4.6985 | 20.01% | 4.6985 | 0.93970 | 65.19 | 0.000 |
| SKIN SITE (F, OA) | 1 | 3.5852 | 15.27% | 3.5842 | 3.58418 | 248.64 | 0.000 |
| SEX | 1 | 0.0037 | 0.02% | 0.0037 | 0.00370 | 0.26 | 0.612 |
| Error | 1054 | 15.1936 | 64.71% | 15.1936 | 0.01442 | | |
| Lack-of-fit | 16 | 1.1860 | 5.05% | 1.1860 | 0.07413 | 5.49 | 0.000 |
| Pure Error | 1038 | 14.0076 | 59.66% | 14.0076 | 0.01349 | | |
| Total | 1061 | 23.4810 | 100.00% | | | | |

Table 2: Estimated Fitted Means.

| Fitted Means | | |
|------------------|-------------|---------|
| Term | Fitted Mean | SE Mean |
| Freq (Hz) | | |
| 5 | 0.22901 | 0.00911 |
| 10 | 0.12131 | 0.00911 |
| 50 | 0.05633 | 0.00911 |
| 150 | 0.05616 | 0.00911 |
| 250 | 0.04787 | 0.00911 |
| 300 | 0.04289 | 0.00911 |

| Skin Site | | |
|---------------------|---------|---------|
| Oral Angle | 0.15036 | 0.00537 |
| Finger (D2, distal) | 0.03417 | 0.00535 |
| Sex | | |
| Female | 0.09029 | 0.00453 |
| Male | 0.09423 | 0.00633 |
| | | |

Discussion

We developed and tested a new application known as VIBROS, using the SIUD adaptive procedure originally described by Lecluyse and Meddis [41] for auditory psychophysics, to estimate vibrotactile detection thresholds of the hairy skin at the oral angle and the glabrous surface of the distal (P4) phalanx of the glabrous index finger. This methodology represents a significant advance to our original report of mechanical frequency detection thresholds in the human hand and face that employed a time-consuming, hardware-intensive, manually executed method-of-limits [43] and extends preliminary work in our laboratory using this SIUD method in neurotypical elder cohorts [42]. The 3-minute 45 second SIUD procedure for the 6 test frequencies selected is efficient as it requires a significantly lower number of trials [41] in order to yield thresholds similar to those attained by traditional methods like the two-interval forced-choice, two-down/one-up and maximum-likelihood procedures.

The number of trials used for VDT estimation in this study ($n = 8$) did not include the false positive or 'catch' trials, and based on the mathematical model published earlier [41] this VDT estimation yields ± 2 dB accuracy. The significant differences in VDT's between the 2 stimulus sites (finger, oral angle) among the neurotypical adults in the present study are consistent with known differences in the representation of mechanoreceptor typing and integument, and result in distinctly unique threshold detection profiles across the vibration test frequencies from 5 to 300 Hz. The present results also are in agreement with microneurographic recordings [44,45] and psychophysical studies in humans [42,43,46], which showed that mechanoreceptive afferents innervating the human perioral facial skin lacked Pacinian-type sensitivity at 250 and 300 Hz [47]. Dependence of VDTs on stimulus frequency and skin site is consistent with the response dynamics and threshold sensitivity of A β mechanoreceptors and unique relations of hairy versus glabrous skin with the surrounding integument. There were no significant differences for hand or face VDTs as a function of sex which is consistent with previously published studies [42,48,49].

A summary of these distinguishing anatomic and physiological properties which influence the contour and absolute VDT sensitivity are detailed in the following sections along with several new applications in haptics which benefit from VDT measurement tools. Skin receives a wealth of stimuli from the environment (touch, stretch, vibration, texture, pressure, itch, heat, cold, and pain)

which are encoded by A β mechanoreceptors located in its layers [1]. Conformational changes to skin during imposed or voluntary movements also results in mechanoreceptor activity and a stream of somatosensory flow along peripheral nerves to the central nervous system [50]. Cutaneous receptors are classified into three groups according to response modality, including (1) mechanoreceptors for stretch, vibration, pressure and touch, (2) nociceptors for pain, and (3) thermoreceptors for heat (unmyelinated C-fibers) and cold (C-fibers and thinly myelinated A δ fibers). Receptors are either *unencapsulated* or *encapsulated* and are in various levels of the skin. Morphology varies from simple naked nerve endings to complex structures [1].

Unencapsulated receptors include free nerve endings, Merkel disc (tactile discs) [51,56] and peritrichial nerve endings at the base of hair follicles. Encapsulated mechanoreceptors include Meissner corpuscles [57-59], Pacinian corpuscles, Krause end bulb corpuscles (temp, pressure especially in lips, tongue), and modified-Ruffini corpuscles [58-61]. Orofacial. The skin surrounding the mouth, cheeks and forehead is derived from the neural crest, and is soft and thin (4-layers), with fine hair and many sebaceous and eccrine sweat glands providing a somewhat oily texture, especially in women [1].

The epidermis ranges in thickness from 0.07 to 0.12 mm and is dominated by keratinocytes interspersed with Merkel cell mechanoreceptors, melanocytes, and other nonepithelial cells. In men, this skin lacks oil but forms many coarse hairs in the chin, cheek, and anterior parts of the lips. The glabrous lip vermillion is devoid of eccrine sweat glands and also thin (~ 1 mm) [1]. Unlike limb muscles, the muscles of facial expression, including the perioral and buccal anatomy, terminate in the dermis. The glabrous lips, perioral hairy skin, oral mucosa, and anterior and dorsum of tongue contain a high density of mechanoreceptors associated with rapidly conducting A β myelinated axons which are responsive to subtle mechanical deformation applied to their receptive fields [62]. The high innervation density of these A β mechanoreceptors is associated with high cortical magnification, defined as the ratio between the areas of representation in the primary somatosensory cortex (S1) to the area of the skin [63]. Perioral skin is predominantly populated with slow-adapting (SA) mechanoreceptors with small receptive fields (2-3 mm) which are well suited to encode facial movements, whereas the tongue tip is dominated by fast-adapting (FA) mechanoreceptors with even smaller receptive fields (~ 1 mm)

[45]. Nordin and Hagbarth [60] described the response characteristics of 84 low-threshold mechanoreceptive afferents innervating facial hairy skin or glabrous lip sampled with microelectrodes from the human infraorbital nerve and found innervation density was highest near the corner of the mouth and on the upper lip.

The activity patterns of single primary SA afferents with large receptive fields were influenced by tangential skin stretch associated with voluntary contraction of facial muscles [60]. These findings suggest that trigeminal mechanoreceptors in hairy and glabrous perioral skin can contribute to facial kinesthesia and proprioception for motor control by signaling small variations in stretching and contraction [50,64]. Hand. In contrast to the face, the skin of the palms and soles, derived from the lateral plate mesoderm, is relatively thick (5-layers, 5+ mm) and glabrous with many eccrine sweat glands, and has individualized sole- and fingerprints that remain unchanged over a lifetime [1]. These skin areas also have a thicker epidermis (0.8 mm on palmar, 1.4 mm on soles) and are designed to tolerate friction and pressure and modulate stiction on smooth surfaces using the sweat glands.

The dermis is approximately 3 mm thick in the palm and tends to be thicker in men than in women. The papillary layer is a thin layer of dermis located immediately beneath the epidermis, and it covers the dermal papillae. The mechanoreceptors of encapsulated Meissner corpuscles reside in some of these papillae and are proximal to the basal lamina. They are sensitive to tactile stimuli of slight deformations in the epidermis and are particularly numerous in the lips, external genitalia, and nipples [1]. Merkel cells are intraepidermal mechanoreceptors that are scarcely distributed in adult skin but are numerous in the glabrous fingertips. Individual Merkel cells are found in close contact with an unmyelinated afferent nerve terminal (nerve plate) and manifest acute sensitivity to light touch [52,65]. They are derived from neural crest cells and another source of epidermal origin [1].

The encapsulated Pacinian corpuscle (PC) is the largest mechanoreceptor found in the dermis close to the hypodermis. Its end organ consists of fluid-filled concentric lamellae which form a capsule over the axon terminal [66]. Over the lifespan, the capsule increases in size and becomes distorted in shape due to the addition of new lamellae around the periphery [67]. The capsule acts as a high-pass filter that limits low-frequency and steady-state pressure stimuli from influencing membrane permeability of the axon terminal, with a best frequency at approximately 250 Hz [68-70]. The anatomic relation of the PC receptor to surrounding integument translates to relatively large receptive fields (several millimeters-to-centimeters in diameter), and well suited for spatial summation [71]. Encapsulated Ruffini corpuscles show directional sensitivity to skin stretch and are in the deepest layer of the dermis known as the reticular layer [1,58-61]. Using microneurography, it has been shown that two types of rapidly adapting units, RA I (Meissner c.) and RA II (Pacinian c.), respond to incipient slippage in the finger-object contact area [73].

It appears that RA I units are the predominant detectors of local slippage and are responsible for grip adjustment, whereas RA II units do not localize partial slippage during precision grip because of their large receptive fields [72]. The interaction of the hand with touched objects results in the propagation of mechanical energy throughout the hand primarily in the 10-100 Hz frequency band which in turn excites mechanoreceptors over wide areas [74,75]), including Pacinian corpuscles owing to their relatively large receptive fields and frequency sensitivity (~20 Hz to 1 kHz) [66,76-80]. Other mechanoreceptors such as Merkel cell neurites (SA I), respond to mechanical inputs over the tactile frequency range [81,82]). Similarly, the numerous Meissner corpuscles (RA I) found in the epidermal grooves of the glabrous skin are most responsive to low-frequency mechanical inputs (10–200 Hz) [83].

Contrasting cutaneous sensitivity of the Hand and Face: The differences in the vibrotactile sensitivities of the hand [43,70,84-86] and face [42,43,87,88] are confirmed in the present report using the SIUD adaptive threshold protocol. The classic Pacinian U-shaped response characteristic in the glabrous hand for vibratory input at 250 Hz is virtually absent in perioral hairy skin [43,44,60,89-91]. This is consistent with histological and physiological studies of facial skin which have not found PC receptors [47,92,93]. The majority of facial muscle fibers insert directly into the skin rather than the connective tissue making it possible for embedded mechanoreceptors such as Ruffini endings to encode proprioceptive information about changes in muscle length and force [50,60].

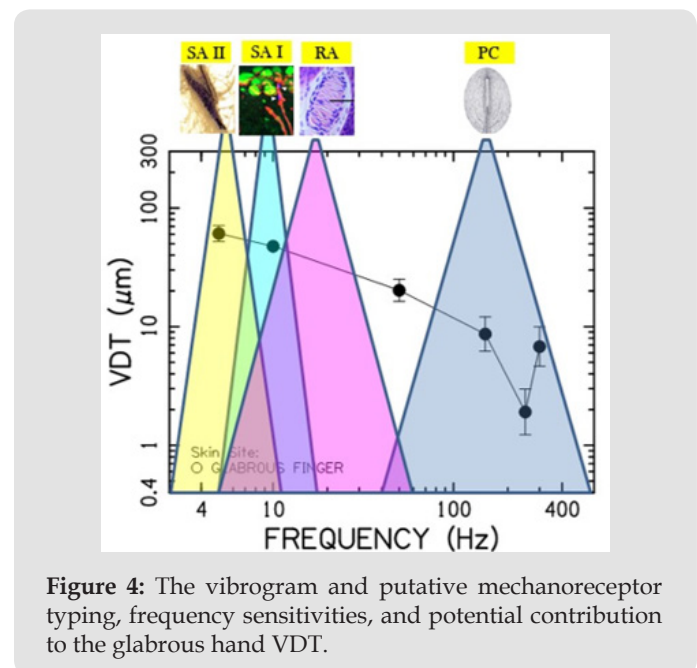


Figure 4: The vibrogram and putative mechanoreceptor typing, frequency sensitivities, and potential contribution to the glabrous hand VDT.

This is interesting given that muscle spindle receptors and Golgi tendon organs, common to limb systems, have not been found in the lower face [94,95]. Mechanoreceptive afferents found in the hand and face can be distinguished by their adaptation profile, best frequency, and receptive field size (Table 3). In a psychophysical vibrotactile detection paradigm such as described in the current report, it is the combination of mechanoreceptor types and their

respective physiological features (adaptation profile, BF, receptive field size, surrounding integument tissue properties, primary afferent projections, functional representation in the brain, and neurological status) which ultimately determine the mechanical frequency detection threshold function for any given skin site, herein known as a vibrogram (Figure 4).

Table 3: Classification of cutaneous mechanoreceptors based on their responses to an applied force, the frequency to which each best responds and the size of their receptive fields.

| Mechanoreceptor | Adaptation Profile | Best Frequency (Hz) | Receptive Field diameter (mm) |
|-----------------------------|--------------------------------------|---------------------|-------------------------------|
| Meissner corpuscle | Rapid-adapting type I (RA I) | < 50 | 1-2 |
| Pacinian corpuscle | Rapid-adapting type II (RA II or PC) | 250 | 8-30 |
| Merkel cell neurite complex | Slow-adapting type I (SA I) | 5-15 | 2-8 |
| Ruffini ending | Slow-adapting type II (SA II) | 0-10 | 2-3 |

As the largest organ of our body, our skin provides tactile channels that can be used for communication in a variety of task-specific haptic interface designs [98]. Haptic sensations offer an additional method of communication between systems and operators in environments in which there is visual or auditory overload [99,100]), including the encoding of touch force over a broad spectrum of inputs (5-1000 Hz) [101], presentation of music spanning musical notes C1 (32.7 Hz) to C6 (1046.5 Hz) as vibration to the glabrous skin to facilitate interaction between musicians with hearing impairments and other musicians during group performances [102], or in mission critical situations in which fighter jet pilot controls utilize a haptic interface that is integrated within an antigravity suit using multichannel vibrotactile inputs (varying in frequency between 27.23 Hz and 152.92 Hz) to the lower back, outer/inner thighs, and outer/inner calves [100].

Brain stimulation techniques guided by tactile sensing technologies are showing promise in neurotherapeutics and functional investigation of the brain [103-105]. For example, some investigators are exploring the effects of transcranial direct current stimulation on neuromodulation of primary somatosensory cortex on VDT detection and somatosensory discrimination [106]. Focused Ultrasound (FUS) sonication of S1 has been used to evoke both sonication-specific electroencephalographic (EEG) responses and various tactile sensations from the hand area of the postcentral gyrus [107]. Others have used mapping of local field potentials to elucidate the functional properties of cortical areas involved in multimodal processing of somatosensory inputs, such as the posterior insula, which is regarded as the so-called 'ouch-zone' and presumed to play a key role pain perception. Direct intracerebral recordings, however, have shown that painful and nonpainful stimuli elicit very similar responses throughout the human insula. Non-nociceptive somatosensory stimuli consisted of 250 Hz vibratory bursts (50 ms) on the palmar surface of the index fingertip [108].

Artificial sensory feedback systems is a rapidly emerging technology which incorporates small vibrating tactors, placed at different parts of the body, to provide spatial as well as temporal

Vibrotactile sensing and emergent haptic technologies. Biological communication modeling and systems design through neurons and networks [96], is engaging haptics to interface brain (mind) and machine, enhance motor control, and develop artificial tactile sensing using 200 Hz probes for object-shape recognition [97] to complement auditory and visual data streams for cyberphysical information flow and smart device control.

feedback to compensate for lost proprioception in individuals with lower-limb impairments [109]. Vibrotactile feedback has demonstrated efficacy in individuals with lower-limb amputations, vestibular impairments, and aging-related loss of balance [110-114]. The targeted vibrations range from 60-400 Hz to match the spectral response profiles of cutaneous mechanoreceptors [110,115,116]. Tracking changes in VDT sensitivity is being used to develop new therapeutic approaches to enhance plantar sensitivity to minimize postural instability in progressive movement disorders such as Parkinson's disease [115]. The modulation of precision grip by anticipatory vibrotaction during 100 Hz and 250 Hz stimulation provides important evidence on the role of mechanoreception to influence motor reflex action during voluntary movement [118]. VDTs obtained using 125 Hz stimuli have been used to follow the progression of peripheral neuropathy in the digits [119].

Conclusion

Our study demonstrated that an automated SIUD adaptive threshold tracking procedure can reliably assess vibrotactile sensitivity for the hand and face in neurotypical adults in a timely manner. This SIUD procedure replicated previous findings which have shown significant main effects for stimulation site and stimulus frequency presumably due to the differences in the density and type of mechanoreceptors innervating the face and glabrous hand. Vibrotactile testing can be used noninvasively map the integrity of A β somatosensory pathways. In our present implementation of the automatic SIUD method, the VDT function at a single skin site based on 6 test frequencies (5, 10, 50, 150, 250, 300 Hz) can be measured in approximately 3 minutes 45 seconds. The range of stimulus test frequencies is user-defined and can be expanded to include 400 and 600 Hz vibratory inputs as well.

The incidence of brain injury and progressive neurological disease increases with age, and the sense of touch is altered in older adults [48,120,121]. Automated VDT testing can be used to determine the extent of sensory impairment, and through repeated measurements monitor the progress of the disease or injury, and treatment efficacy.

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