



Research paper

Vibrotactile and thermal perception and its relation to finger skin thickness

Ronnie Lundström^{a,*}, Håkan Dahlqvist^b, Mats Hagberg^c, Tohr Nilsson^d^a Department of Radiation Sciences, Biomedical Engineering and Radiation Physics, Umeå University, Umeå, Sweden^b ElMeKon HB, Karlstad, Sweden^c Department of Occupational Medicine, Sahlgrenska University Hospital, Göteborg University, Sweden^d Department of Public Health and Clinical Medicine, Occupational Medicine, Umeå University, Umeå, Sweden

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ABSTRACT

Objective: Quantitative measurements of vibrotactile and thermotactile perception thresholds (VPT and TPT, respectively) rely on responses from sensory receptors in the skin when mechanical or thermal stimuli are applied to the skin. The objective was to examine if there is a relation between skin thickness (epidermis and dermis) and VPT or TPT.

Methods: Perception thresholds were measured on the volar side of the fingertip on 148 male subjects, out of which 116 were manual workers exposed to hand-transmitted vibration and 32 were white-collar (office) workers. Skin thickness was measured using a high-frequency ultrasonic derma scanner system.

Results: The difference in age, perception thresholds and skin thickness between manual and office workers was small and non-significant except for the perception of cold, which was decreased by vibration exposure. Skin thickness for both subgroups was mean 0.57 mm (range 0.25–0.93 mm). Increased age was associated with decreased perception of warmth and vibration. Lifetime cumulative exposure to vibration, but not age, was associated with decreased perception of cold.

Conclusion: No association ($p > .05$) was found between finger skin thickness in the range of about 0.1–1 mm and vibration perception threshold for test frequencies from 8 to 500 Hz and thermotactile perception thresholds for warmth and cold. Increasing age was associated with reduced perception of vibration and warmth. Vibration exposure was associated with decreased perception of cold.

Significance: Skin thickness is a factor that may affect the response from sensory receptors, e.g., due to mechanical attenuation and thermal insulation. Thus, to evaluate perception threshold measurements, it is necessary to know if elevated thresholds can be attributed to skin thickness. No previous studies have measured skin thickness as related to vibrotactile and thermotactile perception thresholds. This study showed no association between skin thickness and vibrotactile perception or thermotactile perception.

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1. Introduction

The outcome of vibrotactile and thermotactile perception measurements (VPT and TPT, respectively) is often used for quantitative sensory testing. This involves an integrated response in the brain from cutaneous sensory receptors in the skin in response to mechanical or thermal stimuli to the skin (Lundström, 2002, Nilsson, 2002). Most sensory receptors are located in the dermis (such as thermal receptors, tactile receptors, nociceptors), i.e., between the exterior (epidermis) and the interior (hypodermis) layers, while free nerve endings are also found within the

epidermis. The mechanical or thermal stimulus must be transmitted from the contact point on the skin surface and through the epidermis layer before it can be perceived through evoked activity in suitable receptors. Skin thickness is related to several different factors such as body site, gender, skin type, age, pigmentation and smoking habits (Lee and Hwang, 2002, Sanby-Möller et al., 2003, Waller and Maibach, 2005, Gambichler et al., 2006). The thickness of the epidermis varies in different types of skin, i.e., thinnest on the eyelids (0.05 mm) and thickest on the palms and soles (1.5 mm). The corresponding figures for the dermis are 0.3 mm on the eyelid and 3.0 mm on the back. In addition, if the skin is exposed to heavy, long-term mechanical load, then the thickness of the epidermis will usually increase, most likely as a protective measure. Examples of this are seen among bricklayers

* Corresponding author.

E-mail address: ronnie.lundstrom@umu.se (R. Lundström).

and guitar players. Neurophysiological clinicians and occupational health professionals ask whether the thickness of the skin may affect the person's VPT and TPT. This question does not seem to have been addressed in the scientific literature previously.

2. Objective

The primary objective was to study the relationship between skin thickness and the vibrotactile and thermotactile perception thresholds on the volar side of the right index finger tip. If skin thickness affects the thresholds, then the secondary aim was to discuss how this knowledge should affect clinical practice.

3. Methods

3.1. Subjects

The study was based on a cohort of 229 males, employed either as blue-collar construction workers or as white-collar office workers, at an engineering company that produces heavy equipment for paper and pulp mills. Data for this particular study was collected in May 1997 as a part of a 10-year follow-up. The blue-collar workers performed heavy manual work and were exposed to hand-transmitted vibration (EV). The white-collar office workers sat at desks and were not exposed to heavy manual work or hand-transmitted vibration (NEV). Basic information about age, work assignment, years at work, general state of health, previous and present exposure to vibration was sought in a questionnaire. All participants underwent a medical examination conducted by an occupational physician (TN), and the examination included sensory and motor nerve conduction measurements. Some employees had symptoms of diseases known to cause sensory neuropathies, e.g., diabetes or metabolic disturbances, and were therefore excluded from the study. Electrodiagnostic results indicating sensory block at the wrist and/or clinical symptoms of carpal tunnel syndrome resulted in exclusion. Missing data for vibrotactile perception threshold (VPT), thermotactile perception threshold (TPT) and skin thickness (SkinT) were also cause for exclusion. After applying these exclusion criteria the final study group consisted of 148 individuals, 115 of whom were exposed to, or had been previously exposed to, hand-arm vibration in their work. The lifetime accumulated vibration dose (LTVD) was determined for all of the subjects based on vibration measurements conducted at their work site together with estimation of total duration (questionnaires, diaries and interviews) (Nilsson and Lundström, 2001).

This study was approved by the Regional Ethics Review Board in Umeå, Sweden (Registration number 97-76) and conducted accordingly. All subjects signed an informed consent before entering the study.

3.2. Vibrotactile perception threshold measurement (VPT)

The VPT was measured in accordance with ISO standard 13091-1 (ISO 13091-1, 2001), using a modified version of a von Békésy audiometer (Brüel & Kjaer 1800/WH 1763). The equipment provided a sinusoidal vibration at seven discrete frequencies from 8 to 500 Hz with a magnitude remotely regulated through a button on a hand switch. When the button was pressed, the stimulus amplitude gradually declined, and when the button was released the amplitude gradually increased. The rate of the amplitude change was 3 dB/s. The vibration was delivered perpendicularly from above to the volar aspect of the right hand's index fingertip through a cylindrical Perspex probe with a flat contact surface (diameter 6 mm). The vibration exciter was mounted in accordance

with a beam balance to provide a constant static pressure of 3.5 N/cm² to the skin.

The subjects were asked to sit on a chair with the forearm and the dorsum of the hand resting extended and relaxed on a supportive cushion formed around the person's hand and wrist. The ISO standard 13091-1 (ISO 13091-1, 2001) specifies that VPT measurements should be conducted when the skin temperature at the test location is within the range of 27–35 °C. Therefore, if the subject's skin temperature at the test location was lower than 28 °C, then the hand was warmed with the help of an infrared lamp. The position of the stimulator probe was carefully adjusted so it covered the pulp of the right index finger. The subject was instructed to press the button on the hand switch with the left hand as soon as the vibration to the right index finger was perceived and to keep it depressed as long as the vibration was felt. In this way, the subject's VPT was continuously tracked between the levels for perception and non-perception. The increasing and decreasing level of vibration was recorded as a zigzag pattern, a vibrogram. This psychophysical "up-and-down" threshold tracking method of limits is sometimes called the von Békésy threshold tracking method (For a review, see (Lundström, 2002)). The threshold at each frequency was defined as the average midpoint between the upper and lower limits, expressed in dB relative to 10⁻⁶ m/s_{rms}², (ISO 13091-1). The test equipment software did not automatically compensate thresholds for age or skin thickness.

The vibration perception threshold at different frequencies was conducted in the following ascending order: 8, 16, 32, 63, 125, 250, and 500 Hz. At each frequency, the threshold was tracked for about 30 s with no pauses between frequencies. The whole test took an average of 20 min to perform, including a period of installation, familiarization, and training to obtain stabilized and reproducible threshold levels.

3.3. Thermotactile perception threshold measurement (TPT)

Thermal perception thresholds were determined without automatic software compensation for age or skin thickness using a Somic modification of the Marstock method (Fruhstorfer et al., 1976) with computer-assisted automatic exposure and response recording (Thermotest; Somic, Sales AB, Sweden). A thermostimulator, i.e., a Peltier contact thermode, was applied to the skin. When measuring perception of cold and warmth the probe (25 × 50 mm) was gently applied to the volar surface of the distal and intermediate phalanges of the index finger (lengthways along the finger). Perception thresholds for cold and warmth were assessed using the "Method of limits". The rate of the temperature change was linear and about 1 °C/s. Before the quantitative evaluation of thermal sensibility, the subject's skin temperature at the test site was measured by contact thermometry. This "indifferent" temperature was then used as a neutral starting temperature for the TPT measurements. The lowest acceptable starting temperature was set to 28 °C by applying a similar reasoning as for VPT measurements.

The subject was instructed to press a switch with the left hand when a change of temperature (cold or warmth) was detected after which the temperature of the thermode returned to the pre-set neutral baseline temperature. The measurement of warm and cold thresholds was repeated 10 times. The mean value of these was then calculated. The inter-stimulus interval for all threshold measurements was randomly distributed within 2 s. The operating temperature range was set at 10–52 °C.

3.4. Measurement of finger skin thickness (SkinT)

Skin thickness (SkinT) was measured using a high-frequency ultrasonic scanner system (DermaSCAN C from Cortex Technology,

Denmark), which operates at 20 MHz with a 2D/3D transducer that makes it possible to determine the average distance between different tissue layers. In this case the measurement includes epidermis and dermis due to the small dimensions/distance. By using amplitude detection (A-scan = 1D) due to variations in the tissue response to ultrasound, the echo is converted to a grey scale (256 shades of grey). Setting the sound speed to 1580 m/s gives a resolution area of $60 \times 200 \mu\text{m}$ (axial x lateral) in the focus point and a penetration depth up to 10 mm. Each shade of grey is converted to a color, shown on the display, and these colours do not affect the resolution.

For each subject, two measurements were conducted on the same test spot, one in the lateral direction and one in the distal/proximal direction. The individual finger SkinTs were determined with the built-in data analysis software program included in the ultrasound scanner system. Two measuring callipers were placed on the screen to mark the width of the epidermis plus dermis. (The 1D = A-scan can be used to help identify the cross over or change in acoustic impedance level of two adjacent tissues based on the variance in echo/sound speed when passing through different tissue substances). An application example is shown in Fig. 1. The distance between the callipers is converted to a distance (SI-unit: 10^{-3} m) that is related to the speed of sound in skin tissue (typically 1580 m/s) (Gniadecka et al., 1994). Since the transducer is based on one single crystal, the resolution follows the physical law, which indicates that the resolution is proportional to the frequency. Thus, higher ultrasound frequency provides higher resolution. However, the penetration is proportional to $1/\text{frequency}$. Therefore, the system ultrasound frequency (20 MHz) is optimized due to penetration and resolution against active measuring depth, and this made it possible to measure skin thickness with a resolution of ± 0.02 mm in the beam direction.

3.5. Data analysis and statistics

The study population consisted of both white-collar workers and manual workers. The first step in the data analysis was to determine if any significant differences in TPT, VPT or SkinT measurements between the two subgroups might obstruct pooling of data (Descriptive statistics, Independent samples *t*-tests, repeated measures ANOVA, and simple Cohen's delta tests). The main research question in this study was if TPT and VPT are related to skin thickness and therefore, a linear multivariable regression model was used that also takes other possible covariates into account. In the model, VPT and TPT were designated as dependent variables, and the person's age (Age), finger skin thickness (SkinT) and Life Time accumulated Vibration exposure Dose (LTVD) were independent variables. IBM SPSS Statistics (version 24) was used for all statistical calculations. A $p < .05$ was considered statistically significant.

4. Results

When comparing the vibration-exposed and the non-vibration exposed subgroups, there were only small and non-significant differences regarding age, skin thickness, and VPT for all test frequencies and TPT_W ($p > .05$, Independent samples *t*-test) (Table 1). However, the threshold for TPT_C was 1.2°C lower ($p = .009$) for the blue-collar subgroup, which suggests that heavy manual work and/or exposure to hand-transmitted vibration may decrease the thermal sense for cold. The Cohen's delta values show that the standardized difference between the means for two groups with respect to VPT and TPT_W is descriptively and not inferentially small (for VPT increasing with test frequency from 0.04 to 0.3; $\text{TPT}_C \approx 0.16$). Corresponding delta value for TPT_C is however 0.48 which

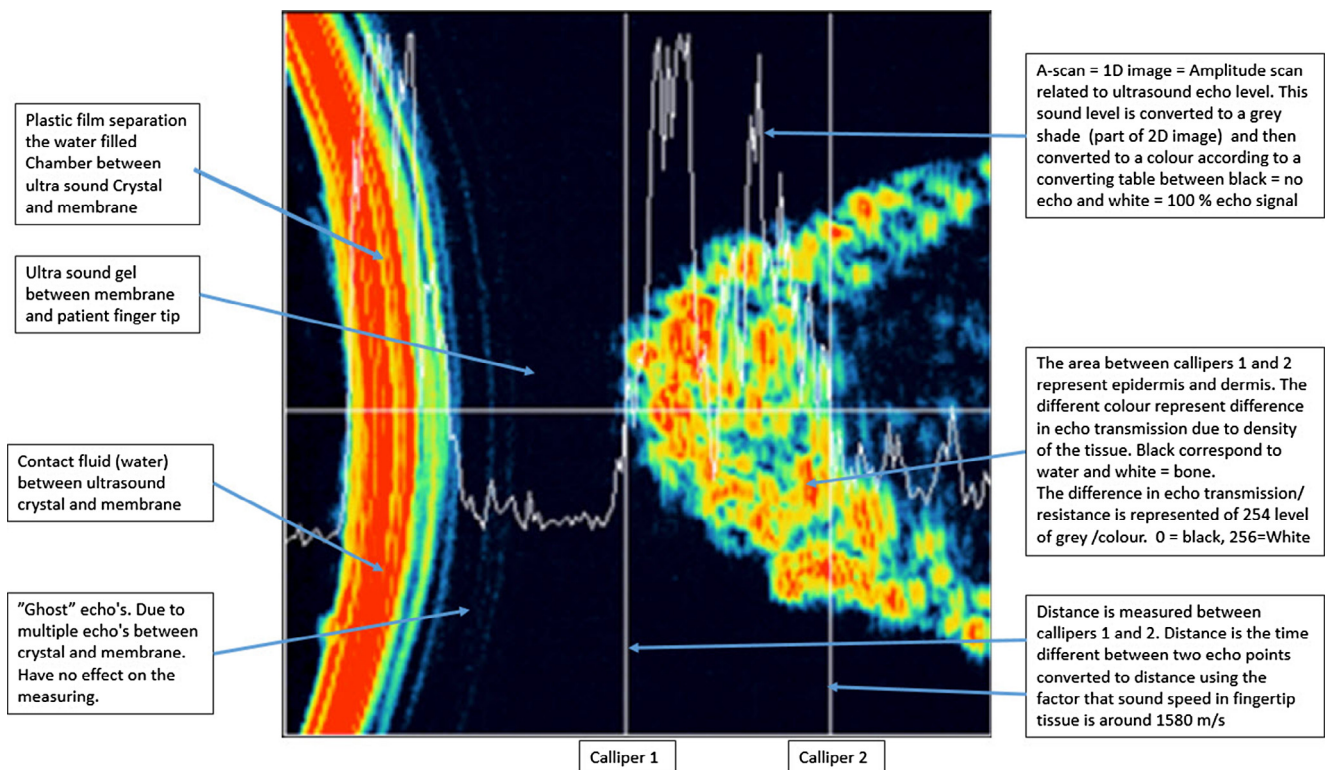


Fig. 1. Image from a skin thickness measurement on one fingertip of one of the subjects. The distance between calliper 1 and 2 is 0.632 mm, which includes epidermis and dermis. For more information, see text.

Table 1
Descriptive statistics for the pooled study group. Statistics: Mean (\pm SD, Min, Max) and independent samples *t*-test (*t*-value and Sig. 2-tailed *p*-value) for exposure categories NEV (*n* = 33 white-collar workers not exposed to vibration) and EV (*n* = 115 blue-collar workers exposed to vibration). Equal variances between categories are not assumed.

N	148 (33/115)	Independent <i>t</i> -test	
		<i>t</i>	<i>p</i> (2-tail)
Age (years)	44.4 (11.7, 23, 64)	1.702	0.095
Vibrotactile perception threshold (VPT), dB (rel. 10^{-6} m/s ²)			
8 Hz	95.5 (4.5, 84.7, 110.0)	0.297	0.768
16 Hz	105.9 (4.8, 92.0, 121.7)	-1.00	0.920
32 Hz	111.3 (5.6, 97.0, 131.0)	-0.630	0.532
64 Hz	112.5 (6.6, 96.7, 141.2)	-1.181	0.242
125 Hz	109.4 (8.3, 91.7, 153.5)	-1.057	0.294
250 Hz	113.9 (9.6, 94.7, 155.7)	-1.624	0.108
500 Hz	130.8 (8.6, 113.7, 160.0)	-1.662	0.101
Thermotactile perception threshold (TPT), °C			
Warmth	35.0 (2.7, 27.6, 43.3, 0.766)	0.996	0.323
Cold	29.6 (2.2, 21.1, 34.2, 0.032)	2.710	0.009
Skin thickness (mm)	0.57 (0.12, 0.25, 0.93)	-0.981	0.330

A *p* < .05 was considered as statistically significant (marked in bold).

indicate a 30% non-overlap of the experimental scores between the two subgroups. In addition, a repeated measures ANOVA show a significant within-subjects difference (i.e. *p* < .000) between VPT's at all 7 test frequencies as well as between the two thermal perception thresholds (TPT_W and TPT_C). No significant interaction effects were however found between groups (i.e. VPT frequency * Group or TPT_C/TPT_W * Group), *p* = .324 and *p* = .553, respectively. The small differences between groups is also visualized by the scatter plots presented in Figs. 2 and 3. Motivated by this result, but keeping the exception for TPT_C in mind, data for each subgroup were pooled and further analysed with respect to the relation between TPT, VPT and SkinT.

4.1. Thermotactile perception versus skin thickness

Descriptive statistics for measured thermotactile perception threshold for warmth and cold (i.e., TPT_W and TPT_C) are presented in Table 1. The average TPT_C and TPT_W are considered normal as

compared with threshold data presented elsewhere (Nilsson et al., 2008).

Scatter plots, linear curve fits and regression coefficients for individual thermotactile perception thresholds (i.e., TPT_W and TPT_C) versus SkinT are shown in Fig. 2 for each sub-group separately as well as all together. The scatter plots and regression coefficients do not indicate any clear relation between TPT_W, TPT_C and SkinT. A multivariable regression analysis for TPT_W and TPT_C is presented in Table 2. Age, SkinT and LTVD were set as independent variables in the regression model. As can be seen, age is the only significant covariate for TPT_W. Age decreases perception of warmth. On the contrary, this is not the case for TPT_C, since age was not a significant covariate. TPT_C seems to be more and equally related to SkinT and LTVD.

4.2. Vibrotactile perception versus skin thickness

Descriptive statistics for measured vibrotactile perception threshold for all seven frequencies (i.e. VPT₈ to VPT₅₀₀) are

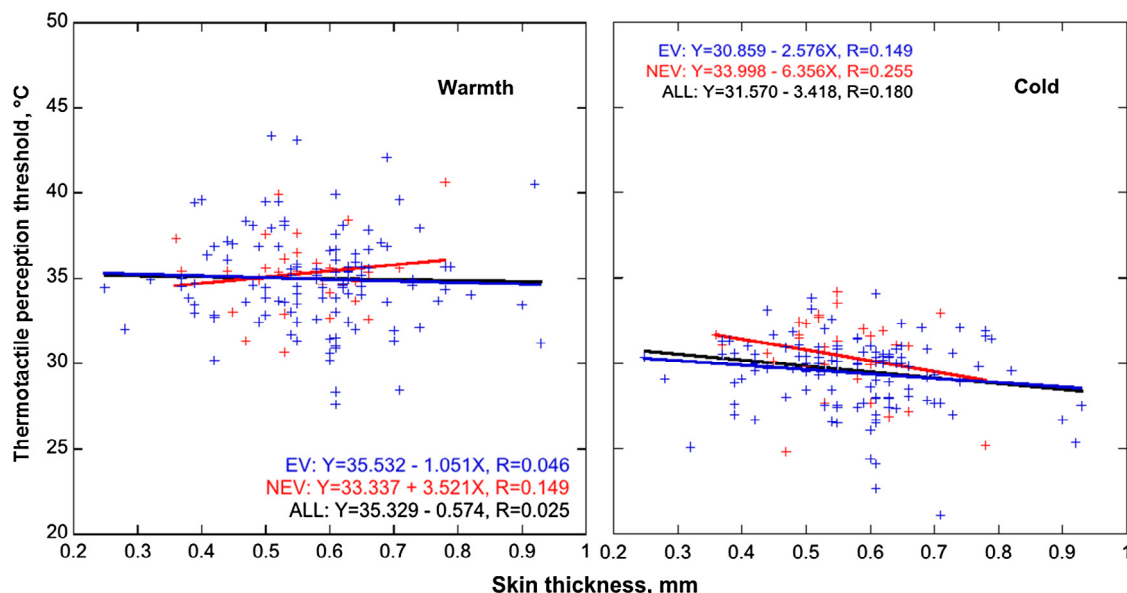


Fig. 2. Scatterplots showing individual thermotactile perception thresholds for warmth and cold versus skin thickness together with linear curve fit data. Red color: White-collar workers not exposed to vibration (NEV); Blue color: Blue-collar workers exposed to vibration and heavy manual work (EV); Black color: All subjects together. For more information, see text.

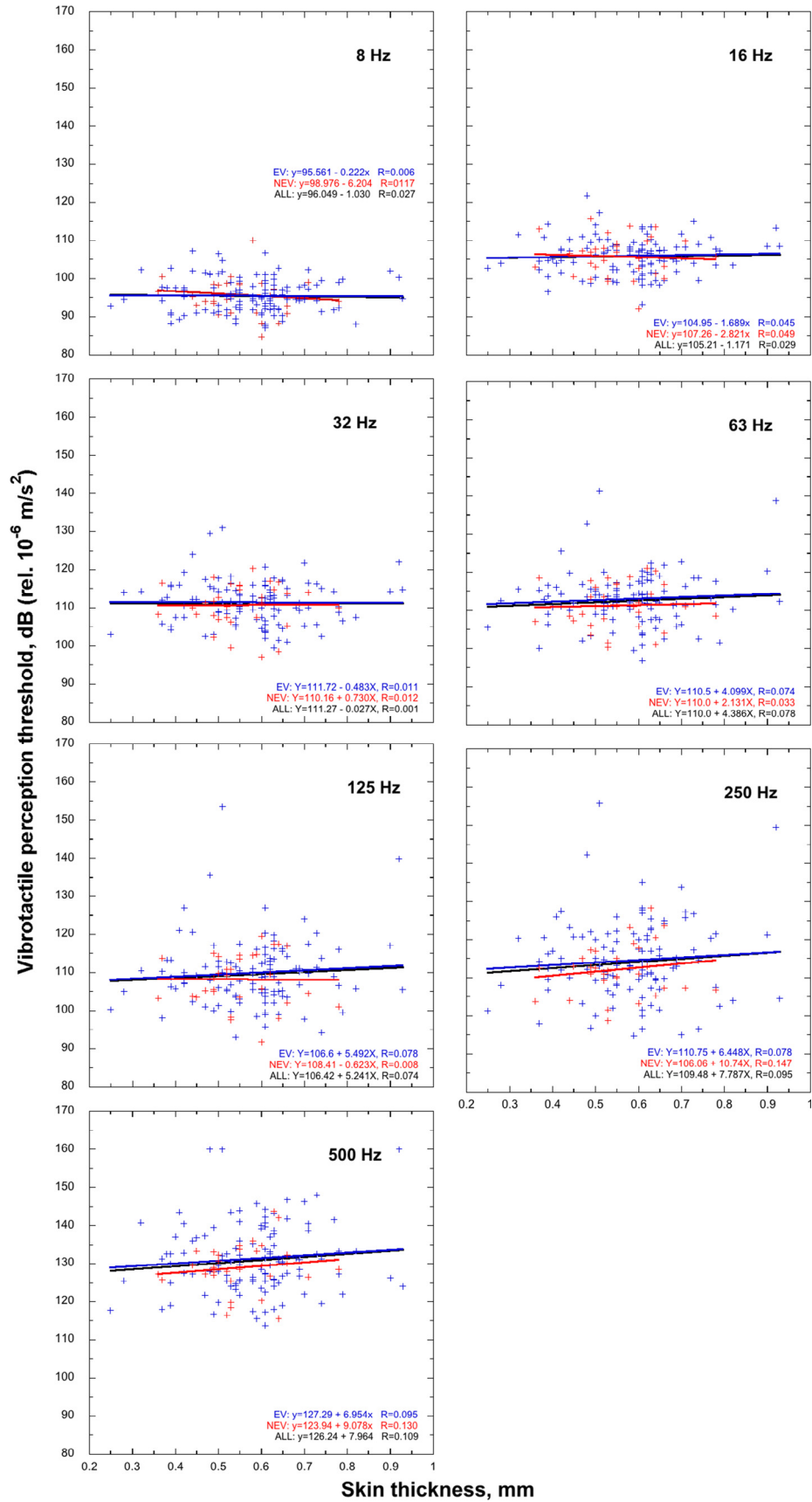


Fig. 3. Scatterplots showing individual vibrotactile perception thresholds at discrete frequencies versus skin thickness together with linear curve fit data. Red color: White-collar workers not exposed to vibration (NEV); Blue color: Blue-collar workers exposed to vibration and heavy manual work (EV); Black color: All subjects together. For more information, see text.

Table 2

Linear multivariable regression statistics with thermotactile (VPT) and thermotactile (TPT) perception thresholds as dependent variables and Age, Skin thickness (SkinT) and Lifetime accumulated vibration dose (LTVD) as independent variables.

		Regression coefficients			t	p
		Unstandardized		Standardized		
		β	SE	β		
TPT _w	Const	33.057	1.419		23.295	.000*
	Age	0.048	0.019	0.208	2.564	.011*
	SkinT	0.101	1.867	0.004	0.054	.957
	Exp	-9.13E-6	0.000	-0.145	-1.787	.076
TPT _c	Const	30.693	1.174		26.138	.000*
	Age	0.019	0.015	0.099	1.223	.223
	SkinT	-2.968	1.545	-0.156	-1.921	.057
	Exp	-8.67E-6	0.000	-0.166	-2.050	.042*
VPT ₈	Const	92.164	2.409		38.265	.000*
	Age	0.081	0.032	0.208	2.560	.011*
	SkinT	0.059	3.169	0.002	0.019	.985
	Exp	-1.3E-5	0.000	0.122	-1.495	.137
VPT ₁₆	Const	99.745	2.500		39.905	.000*
	Age	0.111	0.033	0.271	3.364	.001*
	SkinT	2.209	3.288	0.054	0.672	.503
	Exp	-1.19E-6	0.000	-0.011	-0.132	.895
VPT ₃₂	Const	105.5	2.947		35.813	.000*
	Age	0.117	0.039	0.245	3.017	.003*
	SkinT	1.290	3.877	0.027	0.333	.740
	Exp	-8.01E-6	0.000	-0.061	-0.755	.451
VPT ₆₃	Const	102.2	3.468		29.480	.000*
	Age	0.156	0.046	0.274	3.420	.001*
	SkinT	5.641	4.562	0.099	1.237	.218
	Exp	5.49E-6	0.000	0.035	0.440	.661
VPT ₁₂₅	Const	96.1	4.303		23.3	.000*
	Age	0.212	0.057	0.298	3.738	.000*
	SkinT	7.367	5.661	0.104	1.301	.195
	Exp	-1.03E-5	0.000	-0.53	-0.666	.506
VPT ₂₅₀	Const	93.4	4.774		19.567	.000*
	Age	0.326	0.063	0.398	5.198	.000*
	SkinT	10.702	6.281	0.131	1.704	.091
	Exp	-2.91E-6	0.000	-0.013	-0.169	.866
VPT ₅₀₀	Const	112.8	4.304		26.204	.000*
	Age	0.270	0.057	0.369	4.778	.000*
	SkinT	10.130	5.662	0.138	1.789	.076
	Exp	8.77E-6	0.000	0.044	0.566	.572

A $p < .05$ was considered as statistically significant (marked in bold).

presented in Table 1. The average threshold level for all frequencies is considered normal as compared with a reference population (Lundström et al., 1992). This is also supported by the fact that the calculated sensibility index (SI), in which all test frequencies are included, was about 1.0 (Mean 1.02, SD 0.15) (Lundborg et al., 1992).

Fig. 3 presents scatterplots, linear curve fits and correlation coefficients for VPT's at all 7 test frequencies and their relation to SkinT for each sub-group separately as well as all together. Similar to the results for TPT, it can be clearly stated that VPT levels are not significantly correlated with SkinT (i.e., low linear regression coefficients (R) from about 0.006 to about 0.14. A multivariable regression analysis for VPT is presented in Table 2. Age, SkinT and LTVD were set as independent variables in the regression model. As can be seen, age is the only significant covariate for VPT for all test frequencies. Age decreases the perception of vibration.

5. Discussion

To our knowledge no previous study has specifically addressed the question of whether the thickness of the skin on the volar side of the human fingertip has an influence on vibrotactile or

thermotactile perception threshold levels. We found no association between finger skin thickness within the range of about 0.1–1 mm and vibrotactile or thermotactile perception thresholds.

As mentioned earlier, skin thickness (including epidermis and dermis) varies between different body sites, from about 0.36 mm on the eyelid to 3–4 mm on the back. Skin thickness on the volar aspect of the fingertip was found to be 0.57 mm (SD \pm 0.12 mm). Skin thickness data for the volar aspect of the fingertip seem to be lacking in the scientific literature, and therefore comparisons with corresponding data obtained by others cannot be made. However, it is reasonable to assume that data obtained within this study mirror normal skin thickness.

There are several methodological factors, such as methods of measurement, test site location, skin temperature, probe size, and contact pressure, that may have a significant influence on measured perception threshold levels. For an overview, see e.g. (Lundström, 2002). In this study, all threshold measurements were strictly conducted according to a pre-defined test protocol that kept experimental conditions fixed and included a standardized test procedure. Such methodological factors may give perception thresholds that are either systematically under- or overestimated, but they are most likely in the same order of magnitude. VPT and TPT measurements were also conducted by very experienced medical laboratory technicians, which ensures that the test protocol, including test instructions, training, etc., were administered equally to all subjects. The methodological aspects mentioned above are thus considered to be of no importance for results obtained in this study.

There are also several other factors that may influence a person's vibrotactile and thermotactile perception threshold and skin thickness. It is known that tactile sensitivity decreases somewhat with age (Lundström et al., 1992, Nilsson and Lundström, 2001). It is therefore not surprising that age, as indicated in Table 2, falls out as a significant covariate for most thermotactile and vibrotactile thresholds measured in this study. Thermotactile perception for cold (TPT_c), however, was a clear exception as indicated by the quite different regression coefficients shown in Table 2. Interestingly, age did not fall out as a significant covariate for TPT_c, but vibration exposure did. The other perception thresholds for vibration and temperature were not affected by exposure to vibration.

An extensive data collection protocol was used to uncover each individual's medical history, current health status, thorough physical medical examination, quantitative sensory testing and vibration exposure measurements. A group of white-collar workers with no history of vibration exposure and employed at the same industrial plant served as controls. Follow-up investigations have then been performed at 5-year intervals. During the course of the longitudinal study the study protocol has been held as intact as possible between occasions. However, some parts of the study protocol have been slightly modified, added or excluded for various reasons. For example, skin thickness measurement was added to the protocol at the 10-year follow-up in 1997 due to curiosity about whether skin thickness could influence vibrotactile and thermotactile perception. Another reason was the free access to a novel ultrasonic scanner system. Thus, the reader of this paper must bear in mind that the skin thickness data were collected within the protocol for a longitudinal follow-up study designed for answering a different research question. As authors we are very well aware of the fact that a study specifically designed for the relation between skin thickness and sensorineural perception would have been preferable in this case. One can argue that this study, due to some limitations in the study design, has not been able to provide enough robust evidence that vibrotactile and thermotactile perception are not significantly related to skin thickness. This statement might be relevant, but despite a non-optimized study

design in this case, we are convinced that skin thickness is not a covariant that needs to be considered when evaluating vibrotactile and thermotactile thresholds in a clinical or research setting. This is very important news since it erases a methodological question that has been raised amongst neurophysiologists and occupational health professionals for many years. However, there is still a possibility that other cutaneous variables, such as skin hardness, scarring, previous exposure to thermal extremes, exposure to coarse surfaces or hard pressure might correlate with skin thickness. These issues cannot be addressed here.

6. Conclusion

We found no association ($p > .05$) between finger skin thickness in the range of about 0.1–1 mm and vibrotactile perception thresholds for test frequencies from 8 to 500 Hz and thermotactile perception thresholds for warmth and cold. Age is a covariate for reduced vibrotactile perception and reduced thermotactile perception for warmth. Decreased thermotactile perception for cold is associated with vibration exposure.

Conflict of interest statement

None of the authors have potential conflicts of interest to be disclosed.

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