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Spatial summation of vibrotactile sensations at the foot

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Abstract

Thresholds for the perception of vibration on the hand reduce with increasing area of excitation when the thresholds are mediated by the Pacinian channel (a phenomenon known as spatial summation) but thresholds are generally independent of the area of excitation when they are mediated by non-Pacinian channels. The effect of the area of excitation on vibrotactile thresholds at the sole of the foot has not been thoroughly investigated. In the study reported in this paper, thresholds for the perception of 20-Hz vibration and 160-Hz vibration were determined on the foot (at the big toe (hallux), the medial (inside) ball, the lateral (outside) ball, and the heel) and on the hand (at the thenar eminence and at the fingertip) in 12 male subjects using four probe diameters: 1 mm (0.19 cm^2 excitation area), 3 mm (0.38 cm^2), 6 mm (0.78 mm^2) and 10 mm (1.53 cm^2) with a 2-mm gap between the vibrating probe and a fixed surround. On both the hand and the foot, thresholds for the perception of 160-Hz vibration decreased as the probe diameter increased. There was no overall consistent change in thresholds for the perception of 20-Hz vibration. Thresholds for the perception of 160-Hz vibration were lowest at the fingertip and highest at the big toe. Thresholds for 20-Hz vibration were also lowest at the fingertip. It is concluded that on the sole of the foot there is evidence of spatial summation in the perception of 160-Hz vibration, mediated by the Pacinian channel, but not in the perception of 20-Hz vibration, mediated by a non-Pacinian channel. The findings show that vibrotactile thresholds at the foot obtained with different areas of excitation, or an unknown area of excitation, should not be compared. It is concluded that there is a need to standardise methods of measuring the vibrotactile thresholds at the foot that are obtained for clinical applications.

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1. **Introduction**

Vibrotactile thresholds at the foot are used to monitor diabetic peripheral neuropathy [1]. A wide range of different equipment is used to obtain vibrotactile thresholds at the foot and the absence of suitable standardisation means it is not known whether thresholds obtained by different systems can be compared. Depending on the frequency of vibration, the contact conditions, and some other factors, different tactile receptors and different psychophysical channels are responsible for the mediation of vibration sensations, so different equipment may reflect neuropathy in different physiological processes. The research reported here was designed to provide some of the information needed to standardise conditions appropriate for monitoring neuropathy at the foot when using vibrotactile thresholds.

Most systematic research on vibrotactile thresholds has been undertaken at the hand. Thresholds for the perception of vibration at the glabrous skin of the hand are mediated by four mechanoreceptor channels: a Pacinian channel and three non-Pacinian channels [2-3]. The principal channels are usually the non-Pacinian channel I (NP I channel), generally mediating thresholds from 10 to 40 Hz, and the Pacinian channel having a U-shaped contour of displacement sensitivity over the frequency range 40 to 800 Hz with maximum sensitivity to displacement around 250 or 300 Hz [4-7].

Thresholds for the perception of vibration at the thenar eminence on the hand decrease at a rate of 3 dB per doubling of contact area (from 0.02 to 2.9 cm^2) at frequencies from 80 to 320 Hz, but not at 25 and 40 Hz [2]. The different effects of contact areas at different frequencies is attributed to the differing properties of the channels mediating the perception of vibration. The Pacinian channel (i.e., P channel) has the property of spatial summation, whereas the NP I channel has no spatial summation [2,3,4]. When the contact area at the thenar eminence was sufficiently reduced (from 0.02 cm^2 to 0.005 cm^2), there was no evidence of spatial summation at frequencies greater than 80 Hz [2]. Further studies have found that the perception of vibration with very small contact areas is determined by the non-Pacinian II channel (i.e., NP II channel), which does not have the property of spatial summation [5,6].

Spatial summation has also been observed at the fingertips. Gescheider et al. [7] obtained vibrotactile thresholds with probe contact areas of 0.025, 0.10, 0.38, and 0.75 cm^2 at the fingertip. With 300-Hz vibration, thresholds reduced with a slope of 3 dB per doubling of contactor area between 0.025 and 0.10 cm^2 (probes with diameters of 1.8 and 3.6 mm), but not between 0.38 and 0.75 cm^2 (probes with diameters of 7 and 10 mm). Whitehouse et al. [8] studied vibrotactile thresholds at the fingertip with excitation areas of 0.071 and 0.79 cm^2, and observed lower thresholds with larger excitation areas at 63, 125 and 250 Hz, but not at 8, 16 and 31.5 Hz. Morioka et al. [9] obtained vibrotactile thresholds at the fingertip with excitation areas of 0.071 cm^2 (1-mm diameter probe) and 0.79 cm^2 (6-mm diameter probe)

and found that thresholds at 63, 125 and 250 Hz, where thresholds were believed to be determined by the Pacinian channel, were on average 10.2 dB lower with the larger probe. No spatial summation was observed at 8, 16, and 31.5 Hz, where thresholds were believed to be determined by the NP I channel [9].

There has been little consideration of the effect of contact area on the perception of vibration at the sole of the foot and it is not clear whether the mediation of vibration at threshold is similar to that at the hand. Kekoni et al. [10] found that thresholds at 80 and 240 Hz decreased as the diameter of the vibrating probe increased from 2 to 8 mm. No significant effect of probe size was observed at 20 Hz. Using 1-mm and 6-mm diameter probes (contact areas of 0.071 and 0.79 cm^2), thresholds were lower for most frequencies with the larger contact area at the big toe and lower at all frequencies in the range 8 to 250 Hz at the heel. However, the reduction was only 3.2 dB at the big toe and 6.5 dB at the heel, less than the expected change of more than 9 dB [9].

At the sole of the foot, it is suspected that thresholds for the perception of vibration between about 20 and 40 Hz are mediated by a non-Pacinian channel while the perception of vibration at frequencies between about 40 and 250 Hz is normally mediated by the Pacinian channel [11]. In the glabrous skin of the hand, spatial summation is a characteristic property of Pacinian channel and the absence of spatial summation is characteristic of non-Pacinian channels. At the sole of the foot, spatial summation for vibrotactile thresholds between 40 and 250 Hz would be evidence that over this range of frequencies the thresholds are mediated by the Pacinian channel; conversely, the absence of spatial summation in the frequency range 20 to 40 Hz would be evidence that thresholds are mediated by a non-Pacinian channel.

This study investigated the effects of contact area on thresholds for the perception of 20-Hz and 160-Hz vibration at the sole of the foot, so as to obtain evidence of mediation by the NP I channel and the Pacinian channel, respectively. Thresholds were also obtained at the glabrous skin of hand (at the thenar eminence and at the fingertip) so as to compare the perception of vibration at the sole of the foot with the perception of vibration at the hand. It was hypothesized that for both the hand and the foot there would be spatial summation (with a threshold reduction of about 3 dB per doubling of excitation area) for 160-Hz thresholds, but that there would be no spatial summation for 20-Hz thresholds.

2. Materials and Methods

2.1 Subjects

Twelve male University staff and students (aged 27 ±2 years) with no history of neuropathy participated in the study. The subjects read instructions and gave consent before

commencing the experiment that was approved by the Human Experimentation Safety and Ethics Committee of the ISVR at the University of Southampton.

2.2 Experimental conditions

Using an *HVLab* Vibrotactile Perception Meter (i.e. VPM), thresholds for the perception of 20-Hz and 160-Hz vibration were measured at the fingertip and thenar eminence of the left hand and at four locations on the sole of the left foot: the whorl of the big toe, the whorl of the heel, the medial ball, and the lateral ball. The location of the medial ball of the left foot was defined as 4 cm from the right side of the foot and 4 cm to the rear of crotch of the big toe. The location of the lateral ball of the left foot was defined as 4 cm from the left side of the foot and 4 cm to the rear of the crotch of the little toe.

Thresholds were determined using four circular probes with diameters of 1, 3, 6, and 10 mm, each with a gap of 2 mm between the probe and a fixed circular surround. These four probes provided contact areas (the area of the probe) of 0.008, 0.071, 0.283, and 0.785 cm^2, and excitation areas (the area including the probe and the gap) of 0.196, 0.385, 0.785 and 1.539 cm^2. The force between the surround and the skin was displayed on the front panel of the *HVLab* VPM control box and was controlled by the subjects at 2 N for the fingertip and at 4 N for the other five locations. Subjects adjusted their sitting posture so as to maintain the 4-N force when measuring thresholds at the foot.

FIGURE 1 ABOUT HERE

The applicator was placed on a table when thresholds were obtained at the hand and on the floor when thresholds were obtained at the foot. Subjects sat with the appropriate part of their left hand on the applicator when thresholds were measured at the fingertip or thenar eminence and sat with their left uncovered foot on the VPM applicator when thresholds were measured at the sole of foot. An armrest and a footrest were used to support the arm and foot (Figure 1).

Thresholds were determined using the von Békésy method: the vibration magnitude increased at 5 dB/s until the subject felt the vibration and pressed a response button; the vibration magnitude then decreased at 3 dB/s until the subject could not feel the vibration and released the response button. The vibration magnitude increased and decreased at 3 dB/s as the subject continued to release or press the response button. The measurements continued for a minimum of 30 seconds or until a minimum of six pairs of reversals had been obtained, after excluding the first pair of reversals. Thresholds were determined from the arithmetic averages of the logarithms of the root-mean-square vibration acceleration at the reversals (i.e. a minimum of six reversals).

The experiment consisted of two sessions: one session for measuring thresholds at the big toe, the medial ball, and the lateral ball and another session for measuring thresholds at the

fingertip, the thenar eminence, and the heel. The two sessions, the two frequencies, the three locations in each session, and the four contact areas were presented in a balanced random order.

Room temperature was controlled by air conditioning within the range 24 to 26 °C. Skin temperatures on the fingertip, big toe and the heel were measured using a thermocouple, and were in the range 25.8 to 30.9°C, 26.3 to 30.7°C and 31.9 to 36.3°C, respectively.

2.3 Statistical methods

Experimental results were analysed using the Statistical Package for the Social Sciences (SPSS) version 14.0. Friedman tests and Wilcoxon signed ranks tests were employed to study the difference between different locations and surround conditions. Spearman's rank correlation was employed to investigate any associations between the different thresholds.

3. Results

3.1 Variation in thresholds with contact area

20-Hz thresholds

With 20-Hz vibration, there was no significant difference between thresholds obtained using the 1-mm, 3-mm, 6-mm and 10-mm probes at any of the six locations ($p > 0.05$, Friedman; Figure 2(a)).

FIGURE 2 ABOUT HERE

160-Hz thresholds

At each of the six locations (two on the hand and four on the foot), the 160-Hz thresholds were dependent of the size of the probe and tended to reduce with increasing excitation area ($p < 0.001$, Friedman; Figure 2(b)).

TABLES 1 AND 2 ABOUT HERE

At the big toe, the medial ball, the lateral ball, and thenar eminence, thresholds obtained with the 10-mm probe were lower than thresholds with the 6-mm probe, and thresholds with the 6-mm probe were lower than thresholds obtained with the 3-mm probe ($p<0.05$). There was no significant differences between thresholds obtained with the 1-mm and 3-mm probes at these four locations ($p>0.05$).

At the heel, thresholds obtained with the 10-mm probe were lower than thresholds obtained with the 6-mm probe ($p=0.003$). There was no significant difference between thresholds obtained with 6-mm and 3-mm probe ($p=0.136$), although 9 of 12 the thresholds obtained with 6-mm probe were higher than those with the 3-mm probe. Vibrotactile thresholds obtained with the 3-mm probe were lower than thresholds obtained with 1-mm probe ($p=0.041$).

At the fingertip, thresholds obtained with the 10-mm probe were lower than thresholds with the 6-mm probe, thresholds with the 6-mm probe were lower than those obtained with the 3-mm probe, and thresholds with the 3-mm probe were lower than those obtained with the 1-mm probe (Table 2).

3.2 Variation in thresholds with location on the hand and foot

With 20-Hz vibration, there was a significant difference between thresholds at the fingertip, the thenar eminence and the sole of foot with 1-mm, 3-mm, 6-mm and 10-mm probes (p<0.05; Friedman) Vibrotactile thresholds at the thenar eminence and the sole of the foot were higher than thresholds at the fingertip with 1-mm, 3-mm, 6-mm, and 10-mm probe ($p \leq 0.05$, Wilcoxon).

TABLE 3 ABOUT HERE

With 160-Hz vibration, thresholds with the 1-mm, 3-mm, 6-mm, and 10-mm probes were lowest at the fingertips and highest at the big toe among the six locations (Figure 2 and Table 3).

3.3 Correlations between thresholds with different contact areas

With 20-Hz vibration, thresholds at the sole of the foot obtained with different probe sizes were generally not correlated with each other, but thresholds at the thenar eminence with 1-mm, 3-mm, 6-mm and 10-mm probes were correlated with each other, and thresholds at the fingertip with 1-mm, 3-mm and 6-mm probes were correlated with each other (Table 4). With 160-Hz vibration, thresholds obtained with 1-mm, 3-mm, 6-mm, and 10-mm probes were generally correlated with each other at each of the six locations.

TABLE 4 ABOUT HERE

4. Discussion

4.1 Spatial summation

At the thenar eminence, the 160-Hz thresholds increased as the probe diameter reduced from 10 to 3 mm, consistent with this excitation being mediated by the Pacinian channel [1,4,12]. There was no difference between thresholds obtained with 1-mm and 3-mm probes, consistent with thresholds at frequencies greater than 80 Hz obtained with 1.6-mm and 3.2-mm diameter probes by Verrillo [2]. Thresholds obtained with the 1.6-mm probe by Verrillo [2] were later identified as being mediated by the non-Pacinian channel NP II [5], while the U-shaped tuning curve for thresholds obtained with the 3.2-mm probe suggested they were mediated by the Pacinian channel. In the present study, thresholds mediated by the Pacinian channel when using the 3-mm probe were broadly similar to thresholds mediated by the NP II channel when using a 1-mm probe, although there may be variation between subjects.

With 160-Hz vibration, the dependence on probe size of thresholds at the big toe, medial ball, and lateral ball are similar to that at the thenar eminence: an increase as the probe diameter reduces from 10 to 3 mm but no significant difference between 1 and 3 mm diameter. This suggests 160-Hz thresholds were probably mediated by the Pacinian channel when obtained with 3, 6, and 10 mm probes but mediated by the NP II channel with the 1 mm probe.

At the fingertip, 160-Hz thresholds increased as the probe diameter reduced from 10 to 1 mm, consistent with mediation by the Pacinian channel [7,8,9]. There was a significant difference between thresholds obtained with 1-mm and 3-mm probes, unlike the thenar eminence, because at the fingertip the Pacinian channel is most sensitive even with a 1-mm probe [7]. However, the findings with 3-mm, 6-mm and 10-mm probes differs from Gescheider et al. [7], who found spatial summation only with probes smaller than 3.6-mm diameter (0.10 cm^2 contact area), and no spatial summation with 3.6-mm, 7-mm and 10-mm diameter probes (0.10, 0.38 and 0.75 cm^2 contact area). The difference may be associated with the use of different equipment: Gescheider et al. [7] maintained 0.5-mm pre-indentation of the skin, which was assumed to produce similar pressure between the fingertip and the probe with different probe sizes. In the current study, the pressure between the probe and the fingertip may have been greater with the 6-mm and 10-mm probes than with the 1-mm and 3-mm probes, because the curvature of the fingers may have required subjects to press harder to maintain 2-N force on the surround when less skin was in contact with the surround with the 6-mm and 10-mm probes. Any such increased probe pressure can be expected to have decreased vibrotactile thresholds at the finger with the larger probes [13]. According to the findings of Gescheider et al. [7] and the current study, spatial summation at the fingertip can be confirmed for thresholds obtained with probes less than 3 mm, but the apparent spatial summation at fingertip observed with probes larger than 3 mm may have been caused by increased pressure between the probe and the fingertip with these larger probes.

At the heel, there were differences in 160-Hz thresholds between 1-mm and 3-mm probes and between 6-mm and 10-mm probes, but not between 3-mm and 6-mm diameter probes, although 9 of the 12 subjects showed higher thresholds with the 3-mm diameter probe than with the 6-mm diameter probe. It seems possible that the Pacinian channel mediated 160-Hz thresholds at the heel with all four probes, because some spatial summation was observed.

It may be assumed that the increases in threshold with decreasing probe size were caused by either changes in the number of receptors excited or by changes in the type of receptors excited. Probably, the receptors excited by the vibration were not only those directly adjacent to the probe but also some of those adjacent to the gap between the probe and the

surround. The magnitude of vibration in the skin reduces in some way between the vibrating probe and the stationary surround, so receptors near the probe may be more easily excited than receptors near the surround. The boundary between the receptors that are excited and the receptors that are not excited is not clear, so it is uncertain whether the probe contact area or the area within the surround (referred to here as the 'excitation area') is the appropriate measure of the area of excitation. At the big toe, the ball, and the thenar eminence, there was no significant difference between the thresholds obtained with 1-mm and 3-mm probes, so the rate of change of threshold was investigated only for thresholds obtained with the 3-mm, 6-mm, and 10-mm probes. At the heel and the fingertip, the rate of the change of thresholds was investigated over all four probes. The rates of change of threshold were determined by regression between the logarithm of the acceleration threshold (i.e. the threshold expressed in decibels) and the logarithm of the area (both the contact area and the excitation area):

$$L_T = K_E + r \,.\, \log_{10} A_E$$

and

$$L_T = K_C + r \,.\, \log_{10} A_C$$

where;

L_T = the acceleration threshold (dB re 10^{-6} ms^{-2} r.m.s.)

A_E = the area of excitation (mm^2).

A_C= area of contact (mm^2).

r = rate of change of threshold (dB/mm^2)

giving the results shown in Table 5.

TABLE 5 ABOUT HERE

Although the rates of change of thresholds show spatial summation broadly consistent with the 3 dB per doubling of contact area reported by Verrillo [2], the study does not identify whether thresholds change as a function of contact area or as a function of excitation area.

With 20-Hz vibration, there was no significant effect of probe size (or contact area or excitation area) on thresholds at the big toe, medial ball, heel, or fingertip, consistent with thresholds being determined by the NP I channel [2,12].

4.2 Dependence of thresholds on location

Vibrotactile thresholds at 160 Hz on the big toe were significantly higher than thresholds obtained at other locations, consistent with Kekoni et al. [10] and Morioka et al. [9]. Using 2-mm and 8-mm diameter probes, Kekoni et al. [10] found that 240-Hz thresholds at the big toe and the middle toe were higher than thresholds at other locations on the foot and the

hand. Wells et al. [15] divided the sole of the foot into three anatomical regions of sensitivity: the toes (with highest thresholds), the ball and arch, and the lateral border and heel of the foot. Although there was no significant difference between thresholds at the three regions of the foot, thresholds at the ball, the arch, and the heel were lower than those at the toes with both 250 and 400-Hz vibration in young subjects [15]. Morioka et al. [9] found significantly higher thresholds at the big toe than at the heel and the fingertip with a 6-mm probe at 125 and 250 Hz. Although no significant difference was observed with a 1-mm probe, the median thresholds at the big toe were higher than at the heel. From the analysis above, vibrotactile thresholds at 160 Hz are determined by either the Pacinian or the NP II channel, depending on probe size and contact locations. In the glabrous skin of the hand, the Pacinian channel and the NP II channel have FA II and SA II fibre types, respectively, as anatomical substrates [3,7]. The FA II and SA II fibre types have also been identified at the sole of the foot, with FA II units mainly at the ball and middle toe of the foot, and SA II units across the sole of the foot [9]. Thresholds for the perception of 160-Hz vibration are higher at the big toe than at other locations, which may be because the density of FA II units is lower at the big toe than other locations [16]. Verrillo [2] found that thresholds determined by the NP II channel (SA II units) were independent of contact area. Thresholds obtained with the 1-mm probe at the big toe (probably mediated by the NP II channel) were higher than at the other five locations, possibly because the density of SA II units at the big toe is lower than at other locations. However, the observation of many SA II units over the foot is required to give a clear distribution of the SA II units before the variation in thresholds with the 1-mm probe can be confidently attributed to the variation in the density of SA II units.

The 160-Hz thresholds at the fingertip were significantly lower than thresholds at other locations, consistent with Kekoni et al. [10] and Morioka and Griffin [17]. Kekoni et al. [10] found a difference of about 4.4 dB between fingertip and thenar eminence at 240 Hz. Morioka and Griffin [17] found about 6 dB difference between fingertip and thenar eminence when using a 6-mm diameter probe at 125 Hz, whereas Gescheider et al. [7] found only 3 dB difference between the fingertip and the thenar eminence when using a 7-mm diameter probe and no difference with a 10-mm diameter probe, unlike the 11 dB with 1-mm, 3-mm, 6-mm and 10-mm probes found here. In the current study, the pressure between the probe and the fingertip was greater with the 10-mm probe than with smaller probes because the curvature of the fingers required subjects to press harder to maintain 2-N force on the surround as only limited skin was in contact with the surround. This increased probe pressure can be expected to have decreased vibrotactile thresholds obtained on the finger and the foot with the larger probe [13, 14]. The 160-Hz thresholds at the fingertip and the thenar eminence obtained with 3-mm, 6-mm, and 10-mm probes were probably mediated by the Pacinian channel with the substrate of FA II units. The density of FA II units at the fingertip is about double their density at the thenar eminence [18,19,20], and may also

contribute to the lower threshold at fingertip than at the thenar eminence with the 3-mm, 6-mm and 10-mm probes. Similarly, the thresholds may have been lower at the fingertip than at the foot because there is a greater density of FA II units at the fingertip than at the foot.

The 20-Hz thresholds were lower at the fingertip than at other locations, consistent with Kekoni et al. [10], Morioka and Griffin [17], and Morioka et al. [9]. Kekoni et al. [10] observed lower thresholds at the fingertip than at the big toe and the thenar eminence at 20 Hz but no difference between thresholds at the big toe and the thenar eminence. With 16 and 31.5-Hz vibration, Morioka and Griffin [17] found lower thresholds at the tips of three fingers than at the palm, and with 8, 16, 31.5 and 63 Hz vibration, Morioka et al. [9] observed lower threshold at the fingertip than at the big toe and the heel. The lower thresholds at the fingertip than at the palm may be due to the greater density of FA I units, the substrate of the NP I channel: their density at the fingertip is about seven times their density at the thenar eminence [19]. In the current study, there is generally no difference between the 20-Hz thresholds at the four locations over the sole of the foot, which is only consistent with Kekoni et al. [10]. Wells et al. [15] observed significant differences between thresholds in the three anatomical regions (the toes, the ball and arch, and the lateral border and heel of the foot) at 25 Hz. However, no surround was employed in their study, so it may be uncertain whether the NP I or P channel was responsible for vibration perception at 25 Hz. Morioka [9] found thresholds that were slightly, but significantly, higher at the heel than at the big toe at 16, 31.5 and 63 Hz when using both 1-mm and 6-mm probes. According to Kennedy and Inglis [16], the FA I units are uniformly distributed over the foot, consistent with the present results. However, the quantity of 59 FA I units reported in Kennedy and Inglis [16] may not reflect the full distribution of FA I units, and seems insufficient to predict with confidence whether thresholds over the sole of the foot should be similar or different.

The existence of spatial summation in the perception of 160-Hz thresholds at the sole of the foot is strong evidence that these thresholds were mediated by the Pacinian channel, because only this channel possesses the property of spatial summation. The absence of spatial summation in the perception of 20-Hz thresholds at the sole of the foot is consistent with the 20-Hz thresholds being mediated by the NP I channel.

The presence of spatial summation means that thresholds obtained with different contact conditions cannot be compared. To obtain repeatable and comparable thresholds mediated by both the Pacinian channel and the NP1 channel it will be necessary to standardise the contact conditions, including the size of the vibrating probe and the gap to a stationary surround around the vibrating probe.

5. Conclusions

Spatial summation in the perception of 160-Hz vibration was found at the big toe, the ball of the foot, and the thenar eminence with 3-, 6-, and 10-mm diameter probes, and at the

fingertip with 1-, 3-, 6- and 10-mm diameter probes, indicating that perception of this frequency of vibration was mediated by the Pacinian channel. No spatial summation was observed at the big toe, the ball of the foot, or thenar eminence when using a 1-mm probe, consistent with 160-Hz thresholds being mediated by the NP II channel with this small probe. Thresholds for the perception of 160-Hz vibration at the heel may also be mediated by the Pacinian channel. There was no evidence of spatial summation in the perception of 20-Hz vibration at the big toe, the ball of the foot, the heel, the thenar eminence, or the fingertip, consistent with the perception of this frequency being mediated by the NP I channel.

Thresholds for the perception of 160-Hz vibration are lowest at the fingertip and greatest at the big toe. Thresholds for the perception of 20-Hz vibration are lowest at the fingertip but similar at the thenar eminence and the sole of the foot.

When obtaining thresholds at the foot, the characteristics of the vibrating probe, including the probe diameter and the gap to a stationary surround, should be controlled and defined. There is a need for standardisation of methods of measuring vibrotactile thresholds at the sole of the foot for diagnostic applications.

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Table 1 Median vibrotactile thresholds (ms^{-2} r.m.s.) and inter-quartile range (IQR, 75%-25%) for each location and probe size.

Location		Probe diameter (mm) 1		3		6		10	
		20 Hz	160 Hz	20 Hz	160 Hz	20 Hz	160 Hz	20 Hz	160 Hz
Big toe	Median	0.10	2.73	0.09	2.32	0.14	1.38	0.11	0.63
	IQR	0.06	2.29	0.05	2.90	0.02	1.57	0.06	0.85
Medial ball	Median	0.15	1.12	0.11	1.18	0.12	0.61	0.12	0.36
	IQR	0.09	1.13	0.06	0.89	0.10	0.32	0.05	0.35
Lateral ball	Median	0.13	0.86	0.17	1.01	0.12	0.50	0.09	0.30
	IQR	0.06	0.62	0.09	0.84	0.12	0.44	0.05	0.24
Heel	Median	0.09	0.87	0.14	0.65	0.10	0.55	0.10	0.33
	IQR	0.05	0.95	0.03	0.35	0.08	0.23	0.08	0.22
Thenar eminence	Median	0.09	1.42	0.12	1.25	0.14	0.62	0.08	0.30
	IQR	0.13	1.01	0.13	0.51	0.06	0.21	0.04	0.17
Fingertip	Median	0.04	0.49	0.06	0.35	0.07	0.14	0.06	0.09
	IQR	0.02	0.43	0.02	0.18	0.04	0.11	0.03	0.06

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Table 2 Comparison of vibrotactile thresholds obtained with probe diameters of 1, 3, 6 and 10 mm (Wilcoxon matched-pairs signed ranks: * $p<0.05$; ** $p<0.01$).

		160 Hz		
	Probe diameter (mm)	3	6	10
Toe	1	0.239	0.012*	0.005**
	3		0.002**	0.002**
	6			0.010*
Medial ball	1	0.388	0.084	0.002**
	3		0.010*	0.003**
	6			0.003**
Lateral ball	1	0.530	0.002**	0.002**
	3		0.011*	0.002**
	6			0.008**
Heel	1	0.041*	0.019*	0.002**
	3		0.136	0.010*
	6			0.003**
Thenar eminence	1	0.308	0.003**	0.002**
	3		0.002**	0.002**
	6			0.008**
Fingertip	1	0.015*	0.002**	0.002**
	3		0.002**	0.028*
	6			0.041*

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Table 3 Comparison of vibrotactile thresholds at the six locations (Wilcoxon matched pair signed ranks: * $p<0.05$; ** $p<0.01$).

		20 Hz					160 Hz				
		Medial ball	Lateral ball	Heel	Thenar	Finger tip	Medial ball	Lateral ball	Heel	Thenar	Finger tip
1 mm probe	Toe	0.010*	0.158	0.410	0.638	0.028*	0.002**	0.002**	0.003**	0.034*	0.004**
	Medial ball		0.583	0.530	0.239	0.017*		0.638	0.695	0.388	0.117
	Lateral ball			0.367	0.433	0.005**			0.480	0.239	0.084
	Heel				0.530	0.019*				0.099	0.034*
	Thenar eminence					0.002**					0.002**
3 mm probe	Toe	0.060	0.010*	0.071	0.099	0.023*	0.005**	0.002**	0.003**	0.010*	0.002**
	Medial ball		0.388	0.754	0.937	0.004**		0.239	0.099	0.754	0.010*
	Lateral ball			0.753	0.875	0.005**			0.117	0.388	0.023*
	Heel				0.906	0.003**				0.003**	0.019*
	Thenar eminence					0.005**					0.002**
6 mm probe	Toe	0.347	0.505	0.126	0.432	0.005**	0.034*	0.019*	0.005**	0.006**	0.002**
	Medial ball		0.814	0.209	0.388	0.004**		0.480	0.308	0.347	0.002**
	Lateral ball			0.158	0.289	0.019*			0.388	0.638	0.004**
	Heel				0.783	0.013*				0.814	0.003**
	Thenar eminence					0.006**					0.002**
10 mm probe	Toe	0.844	0.289	0.875	0.110	0.010*	0.060	0.005**	0.008**	0.004**	0.002**
	Medial ball		0.239	0.814	0.158	0.019*		0.117	0.224	0.638	0.002**
	Lateral ball			0.209	0.182	0.025*			0.583	0.638	0.002**
	Heel				0.099	0.006**				1.000	0.003**
	Thenar eminence					0.05					0.034*

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Table 4 Correlation coefficients between vibrotactile thresholds obtained with probe diameters of 1, 3, 6 and 10 mm (* $p<0.05$; ** $p<0.01$).

		20 Hz			160 Hz		
	Probe diameter (mm)	3	6	10	3	6	10
Toe	1	0.084	0.356	0.158	0.580*	0.657*	0.462
	3		0.452	0.256		0.853**	0.937**
	6			-0.133			0.825**
Medial ball	1	-0.053	0.823**	0.189	0.573	0.664*	0.748**
	3		0.200	0.358		0.839**	0.790**
	6			0.298			0.720**
Lateral ball	1	0.396	0.483	0.389	0.958**	0.818**	0.881**
	3		0.350	0.284		0.748**	0.916**
	6			0.834**			0.622*
Heel	1	0.389	0.711**	0.630*	0.741**	0.678*	0.741**
	3		0.434	0.000		0.629*	0.573
	6			0.448			0.503
Thenar eminence	1	0.832**	0.594*	0.720**	0.748**	0.776**	0.441
	3		0.587*	0.608*		0.629*	0.119
	6			0.657*			0.133
	10						
Fingertip	1	0.266	0.237	0.474	0.655*	0.776**	0.895**
	3		0.867**	0.760**		0.347	0.662*
	6			0.782**			0.762**

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Table 5 Reduction per doubling of contact area and excitation area according to the function obtained through regression of 160-Hz thresholds with 3, 6 and 10 mm probes at the big toe the ball and thenar eminence and through regression of 160-Hz thresholds with 1, 3, 6 and 10 mm probes at the heel and fingertip.

Location	Reduction per doubling of area (dB)	
	Contact area	Excitation area
Big toe	2.81	4.92
Medial ball	2.40	4.22
Lateral ball	2.49	4.38
Thenar eminence	3.23	5.62
Heel	1.29	3.01
Fingertip	2.21	5.05

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FIGURE CAPTIONS

Figure 1 Posture of a subject during the measurement of vibrotactile thresholds at the big toe with *HVLab* Vibrotactile Perception Meter (VPM).

Figure 2 Median thresholds of twelve subjects obtained with probe diameters of 1, 3, 6 and 10 mm at 20 and 160 Hz at the big toe, medial ball, lateral ball, heel, thenar eminence and fingertip.

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Figure 1 Posture of a subject during the measurement of vibrotactile thresholds at the big toe with *HVLab* Vibrotactile Perception Meter (VPM).

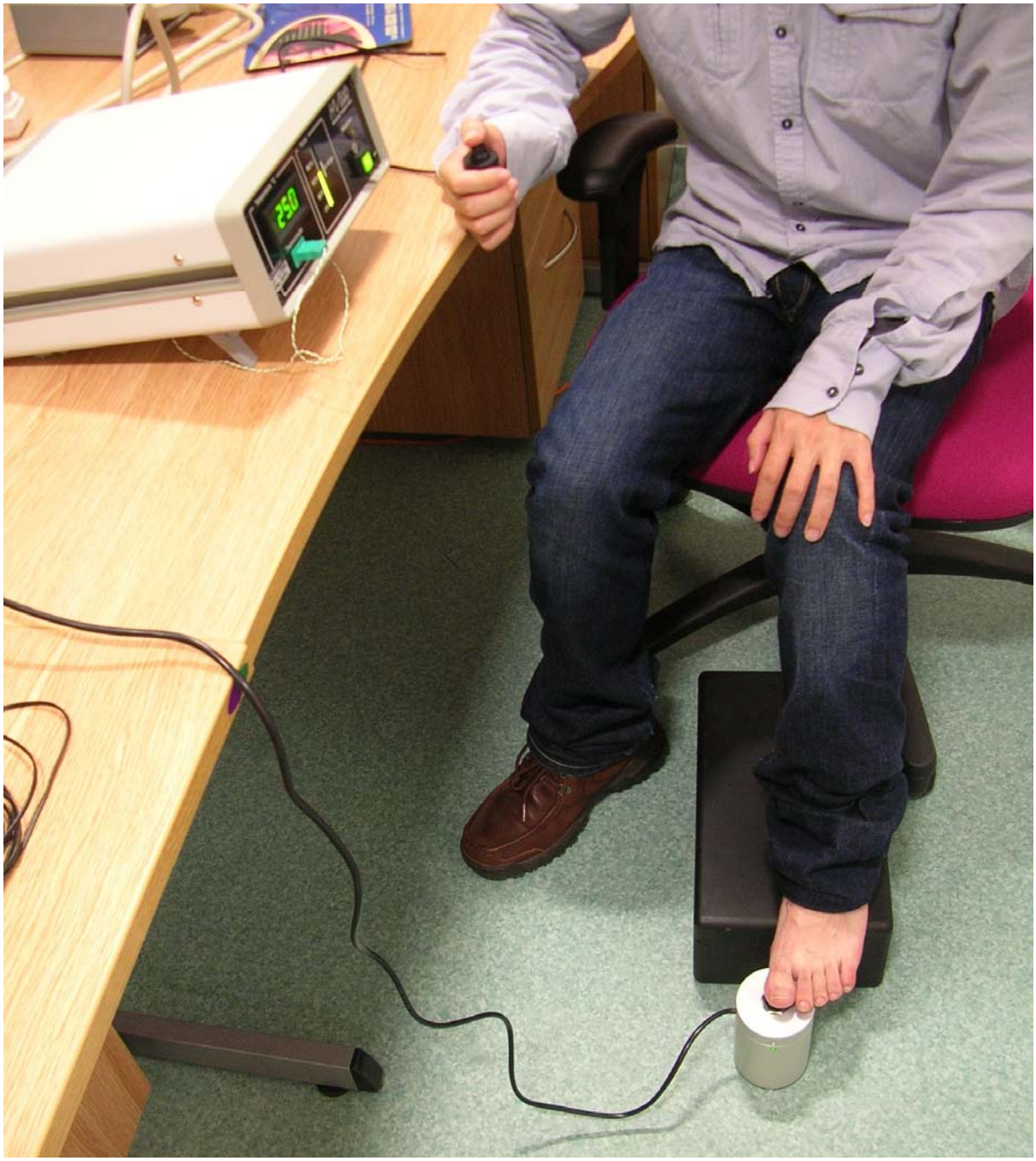

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Figure 2 Median thresholds of twelve subjects obtained with probe diameters of 1, 3, 6 and 10 mm at the big toe, medial ball, lateral ball, heel, thenar eminence and fingertip: (a): at 20 Hz; (b): at 160 Hz. The four probe diameters correspond to contact areas (the area of the probe) of 0.8, 7.1, 28.3, and 78.5 mm^2, and excitation areas (the area including the probe and the gap) of 19.6, 38.5, 78.5 and 153.9 mm^2.