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Vibration perception thresholds of human maxillary and mandibular central incisors

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Normative data

Summary Tactile information from dental mechanoreceptors contributes to the perception of food bolus textures and the control of mastication. While numerous studies have measured the light-touch sensory thresholds of teeth, little information is available about the vibrotactile perception thresholds of teeth. This study uses an adaptive psychophysical procedure to determine thresholds of vibratory stimulation of maxillary and mandibular central incisors in 16 healthy human subjects. An electromechanical vibrator delivered labiolingual forces perpendicular to the long axis of the maxillary and mandibular incisors at 10 stimulation frequencies between 40 and 315 Hz. The median thresholds ranged between 44 and 104 mN. A linear regression analysis revealed a significant increase in the vibrotactile thresholds with increasing frequencies for stimulation of the maxillary and mandibular incisors. No significant differences were found between regression slopes of the thresholds of the maxillary and mandibular incisors. These results indicated that maxillary and mandibular incisors should be able to discriminate effectively among a variety of textures based on their ability to encode a wide range of vibration frequencies.

Introduction

Tactile sensory information from dental mechanoreceptors contributes to the perception of form, texture, and hardness of a food bolus within the oral cavity and to the motor control of the mandible during mastication.[1–3] Abnormalities of the tactile sensitivity of teeth may decrease oral stereognosis[4] and increase bite force.[5,6] Numerous psychophysical studies have attempted to determine the tactile thresholds of teeth to mechanical stimulation [see reviews by Jacobs and van Steenberghe[7] and Linden[1]]. It is generally agreed that most of the mechanoreceptors for light touch sensation involve the slowly adapting mechanoreceptors that are located within the periodontal ligament.[2,8] However, neurophysiological studies in the cat indicate dental mechanoreceptors can also encode vibrotactile stimulation of the teeth[9–11] that likely would involve rapidly adapting mechanoreceptors.[10]

Vibrotactile stimulation of the skin has been implicated in the perception of textured surfaces of objects and as part of the diagnoses of various neuropathies,[12–14] but little information is available about the vibrotactile perception thresholds of

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teeth. Jacobs et al.[15] measured the vibrotactile thresholds of canine teeth at 32, 128, and 256 Hz in three human subjects. The subjects detected all three frequencies, although the thresholds ranged from 85.6 to 105.9 g (839.4—1033.6 mN), which was considerably higher than the reports for thresholds of the light touch mechanoreceptors.[7] Jacobs et al.[15] also found that the threshold at 128 Hz was significantly lower than the thresholds at 32 and 256 Hz, which suggests that dental mechanoreceptors encoding vibration may have a U-shaped, tuning curve similar to Pacinian corpuscle receptors located in the skin.[16] The purpose of this study was to determine the frequency-tuning curve for vibratory mechanoreceptors of human central incisors to mechanical stimulation of a series of frequencies between 40 and 315 Hz.

The vibratory mechanoreceptors may be affected by the biomechanics of the periodontal ligament, since large morphologic differences exist in the root surface areas among different tooth types. Different response characteristics of the biomechanics of the periodontal ligament may explain why the tactile thresholds of anterior teeth are lower than posterior teeth.[17,18] There also are large differences of the root surface areas between maxillary and mandibular teeth. For example, the mean root surface area of maxillary central incisors is approximately 32% larger than the area of the mandibular incisors.[19] By comparing the vibrotactile thresholds of maxillary and mandibular central incisors in this study, the possible influence of tooth root morphology on the dental mechanoreceptors to vibration may also be revealed.

Materials and methods

Subjects

Vibration perception thresholds were determined for a vital maxillary central incisor (#8 or 9) and a vital mandibular (#24 or 25) central incisor in 16 healthy human subjects (13 males and 3 females, 23—35 years of age). The tested teeth were free of dental restorations and the subjects had no dental or orofacial pain, healthy periodontal tissue, and no evidence of peripheral or central neurological disorders. The central incisors were also assessed for vitality with an electric pulp tester (Model 2001, Analytic Technology, 1717 West Collins Orange, CA, USA) and were responsive within the normal range of stimulus intensities. No subjects were excluded based on occlusal relationship, although one subject (# 36) presented with an anterior open-bite occlusal relationship that prohibited anterior tooth contact in maximum intercuspation and in other jaw positions. The Institutional Review Board of the Oregon Health and Science University approved the experimental protocol, which was explained to the subjects who gave their written, informed consent to participate in this investigation.

Apparatus

Fig. 1 shows the components of the experimental set-up. An acrylic stimulus probe with a 2 mm diameter tip was used to deliver labio-lingual forces to the tooth. An electromechanical stimulator (Ling Dynamic Systems Ltd., Heath Works, Baldock Road Royston, Herts SG8 5BQ, England, UK) was used to generate calibrated mechanical stimulus forces. A frequency generator with the impedance matched to the recording attenuator (Model E326A, Grason-Stadler, 5225 Verona Road, Madison, WI, USA) drove the electromechanical stimulator. Dynamic forces were monitored with a piezoelectric force transducer (Model 8001, Bruel & Kjaer, Heinrich-Hertz-Strasse 26, Langen, D-63225, Germany) electrically coupled to a charge amplifier (Model CH-1100, Ono Sokki, 1-16-1 Hakusan, Midori-ku, Yokohama, Japan). Calibration of the piezoelectric force transducer was performed periodically using a reference vibration signal source, which consisted of an electromechanical exciter driven by a stabilised oscillator at 159.2 Hz (Model 84294, Bruel & Kjaer, Heinrich-Hertz-Strasse 26, Langen, D-63225, Germany). The static force of the probe was monitored using a load cell system that included a digital meter and a power supply (ELFS-T3E-2L/RQ and MM50, Entran Devices Inc., 10 Washington Avenue, Fairfield, NJ, USA) and periodically calibrated using known masses. Stimulus force profiles were displayed on a digital storage oscilloscope and the subjects' responses were recorded on strip chart paper. All data were also recorded on magnetic tape.

Procedures

The 90-min experimental sessions included a brief clinical examination and the experimental testing of a maxillary and a mandibular central incisor. After a brief review of the subject's health history, the clinical exam consisted of an inspection of the teeth and periodontal tissues, and palpation of the temporomandibular joints. The data collection took place in a quiet room with the subjects reclined comfortably in a dental chair. The subject's incisors were held in an orthogonal relation to the stimulating probe. The stimulus probe and the teeth were held in a stable relation with silicone rubber impression material (Blu Mousse, Parkell, Farmindale, NY,

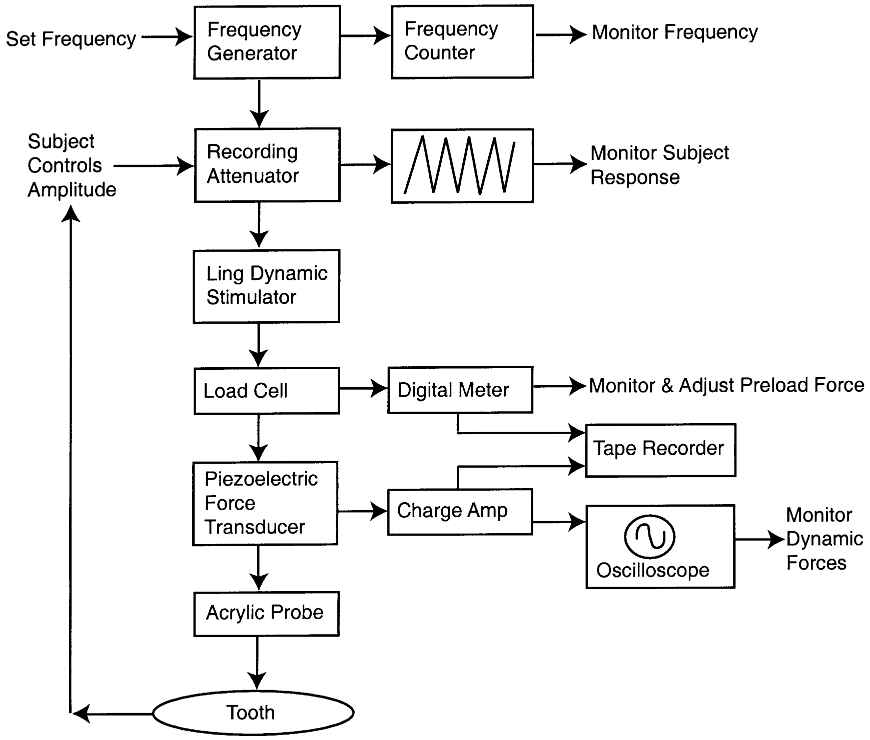

Figure 1 The experimental apparatus consisted of a Ling electromechanical stimulator that was controlled by a frequency generator, in which the experimenter randomly set the frequencies, and an attenuator, which was under the control of the subject. Between the electromechanical stimulator and the acrylic stimulus probe was a load cell, which was used to set a preload force on the tooth, and a piezoelectric force transducer that measured the dynamic stimulus force.

USA) that was attached to a stainless steel bite-fork, which was connected to the stand supporting the stimulus probe. The impression material was trimmed from the central incisors, thereby, allowing the incisors to move freely in response to mechanical stimulation forces.

The stimulus was applied 3 mm from the middle of the incisal edge at force levels between 0.0 and 637 mN. During the application of dynamic stimulation forces, contact of the stimulus probe with the tooth was maintained with approximately 150 ± 50 mN static force, which was based on pilot data that showed lower static force levels resulted in a loss of tooth-probe contact at all but the highest dynamic force levels. Most studies of vibrotactile sensitivity of skin surfaces employ some preload force, although high contract force (e.g. >490 mN) can lead to lower thresholds.[20,21] During data collection, the subjects wore isolation headphones and listened to white noise to mask any auditory components of the test stimuli.

Sinusoidal stimulation forces were presented at ten randomly assigned frequencies between 40 and 315 Hz in 1/3 octave intervals. Subjects were given several practice trials to learn to quickly depress a switch when they first felt the vibration of their tooth. Vibration perception thresholds of maxillary and mandibular incisors were determined using a modification of the von Békésy[22] adaptive psychophysical method, which enabled us to determine the vibration perception thresholds of teeth for a wide range of frequencies within a relatively short time. This stimulation titration method requires the subject to continuously adjust the stimulus amplitude to converge on the upper and lower limits of the stimulus threshold, which is different than the ascending method of limits or the staircase methods where the experimenter adjusts the stimulus amplitude each time the subject does or does not respond to the stimulus. With the von Békésy psychophysical method, the subjects controlled a recording attenuator so that when they sensed the vibration of the tooth they depressed a switch, which decreases the stimulus amplitude, and they released the switch upon cessation of sensation, whereupon the attenuator would increase the signal amplitude until the subject again detected the stimulus. At each frequency tested, the subjects continually adjusted the stimulus amplitude to the high and low limits of threshold range, which typically required about five high and low amplitude oscillations before the subjects achieved a stable level. Once the subjects' high and low oscillations stabilised, three high and three low stimulus amplitudes were measured. The midpoint of the high-low excursion was considered as the vibration perception threshold.[23] A 5-min rest period was provided between the testing of the maxillary and the mandibular incisors.

Data analysis

The means and standard deviations (S.D.) were calculated for thresholds of the maxillary and mandibular teeth for each subject at the 10 test frequencies. A linear regression analysis was used to measure changes across frequencies or between tooth types. An *F* test was used to test the probability that the slope of the linear relationship between threshold and frequency was different than zero (no change) and the differences between the threshold slopes of maxillary versus mandibular incisors. A probability value of less than 0.05 was considered to represent a significant difference.

Results

Across all frequencies and for both tooth types, the vibrotactile perception thresholds were mainly between 44 and 104 mN of peak force, with a few subjects having thresholds between 108 and 441 mN. Consequently, the distribution of responses was skewed toward the lower threshold values, so the data are presented as medians and percentiles (Table 1).

The main question of this study was to determine the type of relationship that exists between the frequency of stimulation and the vibrotactile perception threshold for either the maxillary or mandibular teeth. A linear relationship was found between the stimulus frequency and the thresholds for stimulation of both maxillary and the mandibular incisors (Fig. 2A and B). Significant increases in thresholds across frequencies were evident for both the maxillary ($F_{27.91}$, d.f.$_8$, $P < 0.001$) and the mandibular ($F_{11.49}$, d.f.$_8$, $P < 0.01$) stimulation. The median thresholds ranged from 44 mN at 40 Hz to 104 mN at 315 Hz for the maxillary incisors, which was reflected as a 58% increase in force. The distribution of thresholds to mandibular stimulation was similar to the stimulation of the maxillary incisors, although there was a slight increase in intersubject differences.

A second question of this study was whether the vibrotactile perception thresholds differed between the maxillary incisor with a relatively large root surface area and the mandibular incisor with a smaller root surface area. A comparison was made of the slopes of the thresholds to stimulation of the maxillary and mandibular incisors to determine if the thresholds to the two types of teeth respond differentially to the 10 stimulation frequencies tested (Fig. 2C). The tooth type had no significant effect overall on the threshold levels ($F_{0.403}$, d.f.$_{17}$, $P < 0.533$).

While a goal of this study was to determine the vibrotactile thresholds of normal central incisors (i.e. in dental students with excellent dentention and healthy periodontal tissue), some intersubject variability was evident, particularly among the subjects with high sensory thresholds. Fig. 3A shows representative threshold curves of a subject whose thresholds to maxillary and mandibular stimulation were similar to the group average, Fig. 3B shows the threshold curve of a subject with thresholds generally below the group average, and Fig. 3C shows a threshold-frequency plot of subject with thresholds in the upper quartile for both maxillary and mandibular incisor stimulation. Except for subjects in the upper quartile, the variance was generally consistent across frequencies, except for an increase at

Table 1 Median thresholds (mN force) and percentiles to tactile stimulation of maxillary or mandibular incisors at 10 frequencies for 16 subjects.

Stimulation frequency (Hz)	Maxillary stimulation			Mandibular stimulation		
	Median	25% percentile	75% percentile	Median	25% percentile	75% percentile
40	43.8	26.2	140.5	67.8	41.2	130.5
50	51.5	26.5	105.0	49.9	35.7	97.1
63	70.8	38.5	85.4	37.9	24.7	70.6
80	76.3	34.4	101.7	65.9	25.8	149.6
100	67.1	21.2	148.0	63.9	43.8	106.3
125	80.8	40.0	156.7	77.1	45.2	155.9
160	78.3	33.2	158.8	70.4	30.0	116.7
200	75.0	40.4	171.3	92.1	61.1	135.5
250	102.1	52.9	182.2	108.8	87.1	193.4
315	103.8	56.1	163.4	83.4	45.8	149.2

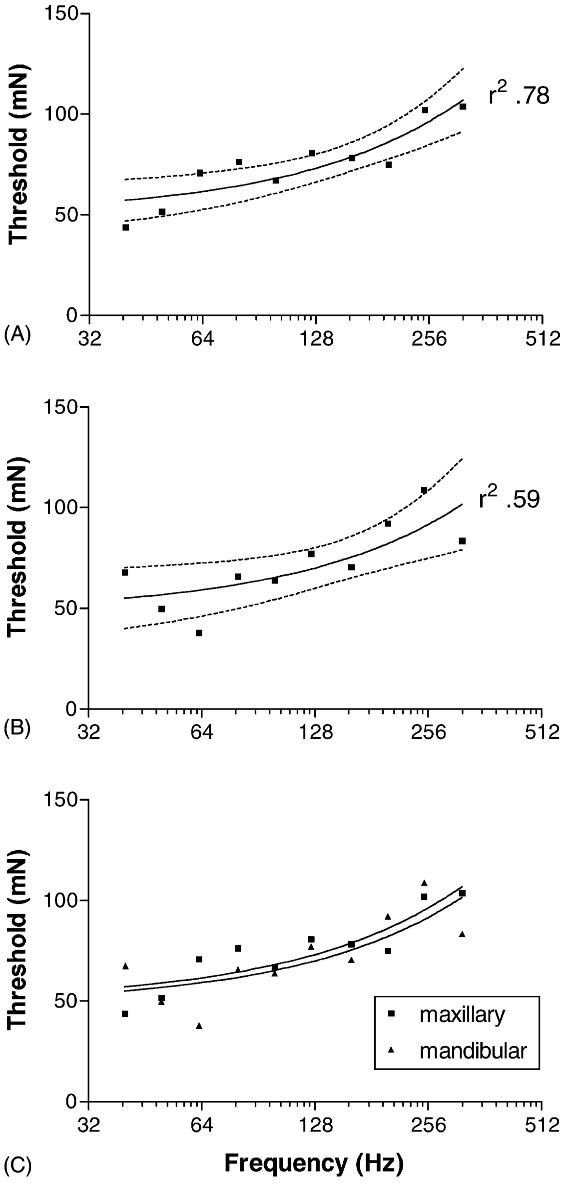

Figure 2 The threshold curves for the maxillary (A) and mandibular (B) incisors at 10 stimulation frequencies on a log scale. The median vibrotactile threshold for 16 subjects is shown at each frequency. Both linear regression lines are significantly different from a horizontal line. The thin dashed lines represent the 95% confidence intervals of the regression line. The linear regressions were not significantly different between maxillary and mandibular stimulation (C).

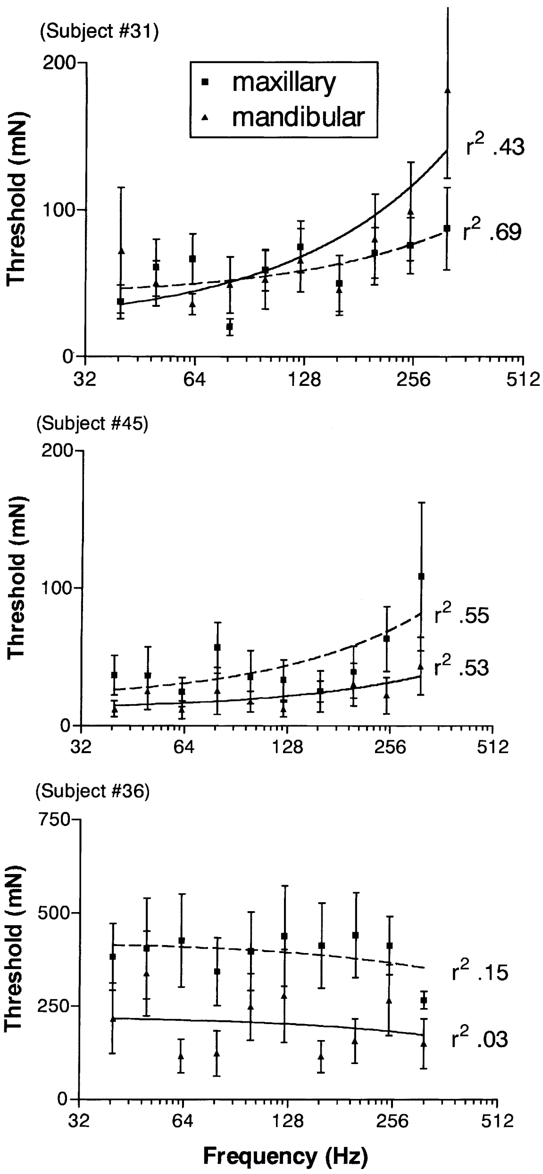

Figure 3 The mean and standard deviations of the vibrotactile perception thresholds of three subjects to stimulation of a maxillary incisor (dashed line) and a mandibular incisor (solid line) at 10 stimulation frequencies. The linear regressions revealed a significant increase with frequency for stimulation of both the maxillary and mandibular teeth for subjects 31 (A) and 32 (B), whereas for one subject (C) the linear regressions did not vary significantly from zero for stimulation of either the maxillary or mandibular incisors.

the two higher frequencies (Fig. 3A and B). Occasionally, a subject had an unexplained high threshold at a particular frequency (Fig. 3A at 32 Hz, 3B at 80 Hz). However, the subjects with thresholds in the upper quartile showed considerable variance at all frequencies, the thresholds did not vary significantly with changes in stimulation frequencies, and the thresholds of the maxillary incisors were an average of 48% higher than the thresholds for the mandibular incisors (Fig. 3C).

Discussion

This study provides the first demonstration of vibration perception thresholds of maxillary and mandibular incisors to a systematic application of sinusoidal vibration between 40 and 315 Hz in young healthy subjects with excellent dentition and periodontonal tissue. Most subjects had low thresholds, between 44 and 104 mN of force, which were considerably lower than the threshold range of 839—1034 mN to vibrotactile stimulation of canine teeth at three frequencies as reported by Jacobs et al.[15] The differences in vibration perception thresholds of this study and the results by Jacobs et al. may be due to several factors. Different types of teeth may have different vibrotactile thresholds that coincide with distinct sensory functions. The maxillary central incisors have lower thresholds than canine teeth to mechanical taps and pressure.[17,24] Different static force levels might affect the vibrotactile thresholds. Most studies of the quantitative testing of vibration threshold employ some static force in order to maintain probe contact with the stimulus site.[20] While the effects of static force on vibration thresholds have not been systematically studied for the teeth, the static force level used in this study or the 49 to 78 mN used by Jacob et al.[15] are considerably lower than the levels used during vibrotactile testing of skin.[20,21] Different psychophysical methods were also employed. Studies that used the ascending or staircase methods of determining thresholds may include errors in threshold determinations due to loss of attention while the subject waits for the stimulus to appear, whereas an advantage of the adaptive psychophysical method, which was used in this study, minimizes errors related to loss of attention by requiring the subject to actively search for the threshold.[23] However, the trial-to-trial variance of both studies was low, which suggests the subjects maintained attention.

Relation between vibrotactile perception thresholds and stimulation frequency

A significant relation between increasing thresholds and higher frequencies of vibratory tooth stimulation was evident for most of our subjects. We found a linear increase in thresholds for stimulation rates between 40 and 315 Hz, which was similar to the frequency tuning thresholds curves of PDL and intradental mechanoreceptors in the cat canine.[10] However, our psychophysical observations and the electrophysiological observations in the cat[10] are in contrast to the observations of vibratory tuning thresholds associated with Pacinian corpuscle receptors that encode cutaneous vibrotactile stimulation.[25] The frequency-tuning threshold curves of Pacinian receptors and vibratory perception are U-shaped and not linear, with maximum sensitivity between 200 and 300 Hz.[16,26] Our findings are also in contrast to observations of Jacobs et al.,[15] who observed that the threshold at 128 Hz was lower than at 32 or 256 Hz, although the frequency tuning curves are difficult to ascertain with data for only three frequencies.

Influence of tooth morphology on vibrotactile perception thresholds

Since the natural or harmonic frequencies of a dynamic mechanical system depend on the mass and viscoelastic damping characteristics of a particular system,[27] we expected that the difference in mass between maxillary and mandibular incisors and the likely difference in the viscoelastic properties of the PDL of the two teeth with different root surface areas would result in differences in thresholds across the three-octave range for the two tooth types. Our data did not support this hypothesis. The vibrotactile perception thresholds and the threshold-frequency linear regressions between maxillary and mandibular incisors were not significantly different, which is similar to previous findings that used a ramp-hold stimulation of the incisor teeth.[17] However, it is probably appropriate that both tooth types convey the similar vibrotactile thresholds, since vibrotactile stimulation of the maxillary and mandibular incisors usually would occur simultaneously when assessing the texture of a food bolus during normal incisor biting.

Other factors that may influence vibrotactile thresholds

Numerous studies of sensory thresholds have described individual differences. Differences in attention, motivation, and cooperation can produce increased variance among individual responses and increased intersubject variance.[28] In the present study, some individuals had low variance at all frequencies, whereas other individuals had large variations in their thresholds at various frequencies, particularly for the three subjects with thresholds in the upper quartile. Our subjects appeared to be very cooperative, motivated, and appeared to attend to the task, so factors such as occlusal relationships, past sensory experiences (including trauma), or subclinical peripheral or central neuropathic changes may explain large threshold variances.

The subject with maxillary thresholds that were more than two standard deviations above the mean (Fig. 3C) had a class I open-bite occlusal relation. Since it was not possible for this subject to occlude his maxillary and mandibular incisors, these teeth would have a different tactile sensory experience than in a normal occlusion. The absence of the normal everyday tooth contacts that occur during biting, chewing, swallowing and speech may have resulted in a deficit in making vibratory discriminations with his incisors. There is a growing body of evidence that various levels of the somatosensory system are dependent on environmental experiences.[29,30] Consequently, the perception of vibration of the central incisors may vary among individuals depending on the past sensory experiences.

Possible mechanoreceptors

Perceptually, vibration of the human skin is typically divided into two separate sensations—flutter that occurs at frequencies less than 40 Hz and vibration that spans the range from 40 to 400 Hz—that are generally considered to be conveyed to the nervous system by large, myelinated Aβ fibres, with conduction velocities of more than 30 m/s.[25] The mechanoreceptors of the human skin that best encode flutter are the Meissner corpuscle, whereas the Pacinian corpuscles respond to vibration.[25] However, neither Meissner nor Pacinian corpuscles have been identified in the PDL or the tooth, so it is not yet clear how vibration sensation of the human teeth is achieved. The mechanoreceptors within the PDL are Ruffini endings that have slowly and less often, rapidly adapting discharge properties.[10,31] It is also likely that the slowly adapting mechanoreceptors were not responsive to vibratory stimuli, since these mechanoreceptors would be expected to respond to the static qualities of the preload force. This suggests that a distinct population of dental mechanoreceptors can encode vibration. Dong et al.[10] suggested that free nerve endings of the Aβ fibers within the tooth may be capable of encoding the transmission of vibration through enamel to the dentinal fluid, although other investigations have not supported this hypothesis.[32,33]

The sinusoidal stimulation may have also elicited, via bone conduction, receptors in the middle ear, stretch receptors in the jaw closing muscles, or mechanoreceptors located in other structures of the oral and perioral areas, such as in the hard palate and the temporomandibular joint capsule.[34–37] It is unlikely that any auditory receptors were elicited, since these receptors were probably masked by the white noise presented during testing. Mechanoreceptors located solely within the palate, jaw-closing muscles, or joint probably are not sufficient to encode vibrotactile stimulation for both the maxillary and mandibular incisors, since the vibrotactile thresholds were similar between the maxillary and mandibular incisors. However, the vibration perception thresholds may have been influenced by interdental contact of the test-incisor with neighbouring teeth,[38,39] since interdental contacts may have allowed the activation of neighbouring mechanoreceptors or may have resulted in the spatial summation of afferent input.

Acknowledgements

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