Evaluation of the Human Subject's Ability to Differentiate Intensity of Forces Applied to the Maxillary Central Incisors

Douglas C. Bowman and Patrick M. Nakfoor

J DENT RES 1968; 47; 252
DOI: 10.1177/00220345680470021001

Evaluation of the Human Subject's Ability to Differentiate Intensity of Forces Applied to the Maxillary Central Incisors

DOUGLAS C. BOWMAN and PATRICK M. NAKFOOR

Departments of Physiology and Orthodontics, Loyola University School of Dentistry, Chicago, Illinois

Minimal detectable differences between two centered forces applied to maxillary central incisors were determined for 50 subjects. The forces involved were 10, 50, 100, 200, 500, and 1,000 gm; most accurate subjective discrimination was between the 50- and 500-gm centered forces. Incisally and labially directed forces yielded nearly identical results.

Investigators have applied forces to teeth and reported threshold values for conscious awareness in human subjects[1,2] and for induction of electrical impulses along afferent nerves innervating the periodontal ligament of experimental animals.[3,4] Investigators also have used various gnathodynamometers to determine the maximum force that individuals can voluntarily impart to the teeth.[5,6] However, no one has quantitatively evaluated the ability of the individual to discrimate between forces of different intensity; neither has anyone ascertained what forces applied to the teeth are optimal for the functioning of neural receptors in the periodontal ligament.

Weber,[7] studying the lifting of weights, recognized that there must be a sufficiently large difference between two weights before they could be distinguished as separate. Fechner,[8] on the basis of his own observations and the previous reports of Weber, derived a ratio between the intensity of the stimulus used (I) and the change in this stimulus (dI) before a difference between the two could be detected. This ratio, referred to as Weber's law, may be mathematically expressed as $C=\frac{dI}{I}$. Fechner, extending this concept still further, formulated what has become known as the "psychophysical law," which states that perceived sensation increases proportionally to the logarithm of the intensity of the stimulus. Mathematically, this may be expressed as $S=A \log I+K$, where I equals the intensity of the stimulus, S equals the intensity of the perceived sensation, and A and K are constants needed to relate I to S.

The early history of these concepts is reviewed by both Thurstone[9] and Boring.[10] Stevens,[11] the most ardent critic of the Fechner psychophysical law, has shown that, for 12 different continua of stimuli, the subject's perception grows as a power function of the stimulus intensity. This can be expressed by the general equation $dS=kI^X$. Treisman,[12] summarizing the results and observations of a number of investigators, asserted that the Weber law and its subsequent mathematical expressions are valid only for the middle range of stimulus intensities. The numerical values of the Weber ratio increase in both the low and the high range of stimulus intensities.

Kawamura and Watanabe[13] have reported a Weber ratio for proprioceptive sensation for human teeth. This was accomplished by having subjects discriminate differences in the diameters of two wires placed between the teeth and bitten on with voluntary force. They established a differential threshold (Weber ratio) of 0.1 for 100% discrimination between wires of two different diameters.

Materials and Methods

The 50 subjects in this study were selected from patients at the Department of Orthodontics at Loyola University, School of Dentistry. All data were recorded for the maxillary central incisor teeth.

Forces were delivered by means of a specially designed force-producing instru-

Received for publication July 27, 1967.

ment.* This instrument allowed force to be applied to any surface of the tooth and to be directed along any plane. The versatility of the instrument was derived from the arrangement of its components, a torque wrench with its adaptor and the fixture on which it was mounted. A torque wrench measures resistance to turning encountered at the drive square. In this study, the torque wrench was modified by having its drive square coupled with a bearing and drive shaft assembly. This allowed for a nearly frictionless movement as the drive square rotated through 360°. A 12-inch lever arm, having a balancing counterweight on one end and an adjustable pointer on the other, was attached to the rotating drive square. The relationship of the tip of the pointer to the long axis of the crown of the tooth predetermined the angle at which the force was directed. The scale readings on the torque wrench handle represented the amount of force applied to the tooth. Four different torque wrenches were employed for this study. The overall error was calculated to be less than 2% of the stated force.

The examining room was 7 feet square, well lighted and air conditioned. The subjects were seated comfortably in a dental chair and the procedure was explained to them. The subjects' arms were used to demonstrate to them what they would feel: They were instructed that they would feel two pushes and hear the comments, "This is the first force," and, "This is the second force," and that they would then be asked to identify the heavier force. These two demonstration forces were always distinguishable by the subject. After this introduction, they were told that their teeth would receive forces in a similar manner. The procedure was then repeated using the torque wrench assemblage.

Forces were applied in two directions in all subjects. One series of forces was applied to the incisal surface and directed along the long axis of the central incisor. The second series of forces was applied to the labial surface and directed 90° to the long axis.

The standard force values used were 10, 50, 100, 200, 500, and 1,000 gm. Differential thresholds were established for each of these forces for each subject. This was accomplished by first using a differential threshold of ± 10% of the standard values and by then increasing or decreasing the comparative force until the individual could compare it with the standard force. The validity of the differential threshold was established by the individual's correct identification of the heavier of two forces in at least seven of ten comparisons. If the subject could not correctly identify the heavier force at least 70% of the time, the differential threshold was considered too low and was increased until the subject could identify the heavier of the two forces at least seven times out of ten. This value was then accepted as the differential threshold for that subject. If the subject correctly identified the heavier force for all ten comparisons, the determined differential threshold was considered too high. A lower differential threshold was established by decreasing the force differential compared to the standard force.

The pattern of tooth stimulation was considered important. It was possible to develop a rhythm that permitted nearly equal intervals for each of the standard forces and the comparative forces by practicing the application of the various forces with the aid of a metronome set at two beats per second.

Results

The mean Weber ratios for the standard forces used are shown (Table 1) both for forces applied to the incisal surface of the maxillary central incisor and directed along the long axis of the crown and for forces applied to the labial surface and directed 90° to the long axis. Differentiation was poor when light forces were applied to the teeth. The difference in intensity of the two forces that were centered around 10 gm was, on the average, more than 45% before differentia-

TABLE 1
MEAN WEBER RATIOS DETERMINED FOR VARYING FORCES APPLIED TO MAXILLARY CENTRAL INCISORS IN 50 SUBJECTS

Standard Force Value (gm)	Force Application: Labial Surface; Directed 90° to Long Axis	Force Application: Incisal Surface; Directed Along Long Axis
10	0.453 ± 0.168*	0.467 ± 0.053
50	0.133 ± 0.032	0.132 ± 0.036
100	0.135 ± 0.037	0.137 ± 0.041
200	0.126 ± 0.031	0.124 ± 0.030
500	0.105 ± 0.032	0.108 ± 0.031
1,000	0.195 ± 0.035	0.179 ± 0.047

* Mean ± 1 standard deviation.

* Designed and constructed by the P. A. Sturtevant Co., Addison, Ill.

tion was successful. When the standard force values were centered around 50, 100, 200, or 500 gm, the Weber ratios were much lower and fairly consistent, ranging from 0.105 to 0.135 for forces applied 90° to the long axis of the crown and from 0.108 to 0.137 for forces applied along the long axis of the crown. The Weber ratios increased greatly for the 1,000-gm-centered forces.

The statistical comparisons of Weber ratios for the various force-centered stimuli are presented in Table 2. Only the com-

TABLE 2
STATISTICAL COMPARISONS OF WEBER RATIOS FOR VARIOUS STANDARD FORCE APPLICATIONS TO MAXILLARY CENTRAL INCISORS

	t Values	
Comparisons of Force (gm)	Force Applied on Labial Surface; Directed 90° to Long Axis	Force Applied on Incisal Surface; Directed Along Long Axis
10 vs 50	6.39‡	5.95‡
10 vs 100	6.41‡	6.22‡
10 vs 200	7.77‡	6.04‡
10 vs 500	6.41‡	5.93‡
10 vs 1,000	6.00‡	5.76‡
50 vs 100	0.44	2.39†
50 vs 200	1.42	0.21
50 vs 500	2.76†	3.11†
100 vs 200	1.67	3.95‡
100 vs 500	3.67‡	4.18‡
200 vs 500	2.77†	2.49†
50 vs 1,000	7.84‡	6.32‡
100 vs 1,000	6.38‡	5.00‡
200 vs 1,000	5.95‡	5.48‡
500 vs 1,000	6.55‡	5.55‡

* 0.05 > P > 0.01. † 0.01 > P > 0.001. ‡ P < 0.001.

parisons of 50 versus 100 gm, 50 versus 200 gm, and 100 versus 200 gm. for forces applied 90° to the long axis and 50 versus 200 gm for forces applied along the long axis did not show a statistical significant difference. The Student's *t*-test values involving comparisons with the 10-gm-centered forces or the 1,000-gm-centered forces were higher than those comparisons among the forces centered around 50, 100, 200, and 500 gm.

Since the Weber ratio is now generally recognized not to be constant over a wide range of stimulus intensities, it was decided to test the fit of these data to the two most widely accepted mathematical expressions of this psychophysical phenomenon, the Fechner logarithmic equation and the Stevens power equation.

If the Fechner logarithmic equation ($S=A\ log\ I+K$) is the more applicable expression for this study, plotting the differential threshold (ie, the actual minimal discernible difference, in grams, between the two forces) against the logarithm of the stimulus force should provide the better fit of the data. This plot is shown for forces applied to the incisal edge of the tooth and directed along the long axis of the crown (Fig 1) and for forces applied to the labial surface of the tooth and directed 90° to the long axis (Fig 2).

If the Stevens power equation ($dS=kI^X$) is the more applicable expression for this study, plotting the logarithm of the differential threshold against the logarithm of the stimulus force should provide the better fit of the data. This plot is shown for forces applied to the incisal edge of the tooth and directed along the long axis of the crown (Fig 3) and for forces applied to the labial surface of the tooth and directed 90° to the long axis (Fig 4).

The logarithmic plots in Figures 3 and 4 showed a more nearly linear relationship between the standard forces centered around 50 and 500 gm than did the semilogarithmic plots in Figures 1 and 2. From this, it can be concluded that the data obtained in this study better satisfy the Stevens power expression than the Fechner logarithmic expression. These plots of the Stevens power equation also demonstrate that forces centered around 10 and 1,000 gm are outside the optimal functioning range of the sensory receptors of the periodontal ligament.

The statistical evaluation of the differential equation of the Stevens power expression $dS=kI^X$ to fit the data can be accomplished in this manner: First, it is assumed that only the forces centered around 50, 100, 200, and 500 gm are within the optimal functioning limits of the psychophysical phenomenon. The equation then can be changed to the logarithmic form, $log\ dS=log\ k+X\ log\ I$ and then by rearranging:

$$X=\frac{log\ dS-log\ k}{log\ I}$$

where I equals the applied force and dS equals the differential threshold determined for that force. Since the exponent X is considered a constant throughout the functional range of the equation, any two equations for stimulating forces within these limits can be set equal as:

$$\frac{log\ dS-log\ k}{log\ I}=\frac{log\ dS'-log\ k}{log\ I'}$$

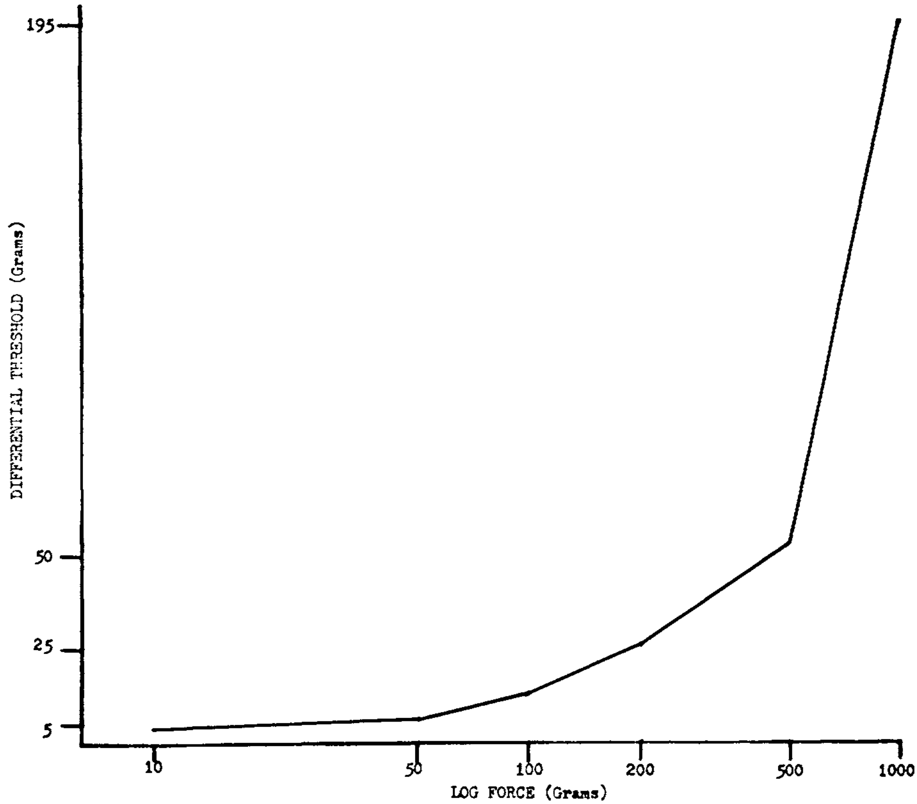

FIG 1.—Mean differential threshold plotted against logarithm of applied force for forces applied to incisal surface and directed along the long axis of the crown.

where I equals one force and dS the differential threshold for that force, and I' equals the second force and dS' equals the differential threshold determined for that force. *Log k* was found from this by solving the equations for all comparisons of mean values between the 50-, 100-, 200-, and 500-gm forces. The mean values of k, determined by this procedure, were calculated to be 0.23 for forces applied along the long axis and 0.24 for forces applied 90° to the long axis.

The X values were then calculated for each subject at each force application. These mean exponential values and their standard deviations are presented (Table 3). The t comparisons of these calculated X values between the various forces applied were then determined (Table 4). The t values for comparisons that involved the 10-gm forces were 12.256 to 18.431. The t values for comparisons 1,000-gm forces were 9.183 to 43.400. The t values for comparisons between forces centered around 50, 100, 200, and 500 gm were 0.446 to 2.985, and only the comparison of 50 versus 500 gm showed a statistically significant difference for forces applied 90° to the long axis. The values for the t compari-

TABLE 3
MEAN VALUES OF X DETERMINED FROM THE EQUATION $dS = kI^X$ FOR EACH OF 50 SUBJECTS

	X Values	
Standard Force Value (gm)	Force Applied on Labial Surface; Directed 90° to Long Axis (k = 0.24)	Force Applied on Incisal Surface; Directed Along Long Axis (k = 0.23)
10	1.251 ± 0.155*	1.308 ± 0.150
50	0.847 ± 0.059	0.838 ± 0.067
100	0.871 ± 0.063	0.862 ± 0.062
200	0.866 ± 0.048	0.878 ± 0.054
500	0.876 ± 0.037	0.866 ± 0.050
1,000	0.974 ± 0.029	0.966 ± 0.030

* Mean ± 1 standard deviation.

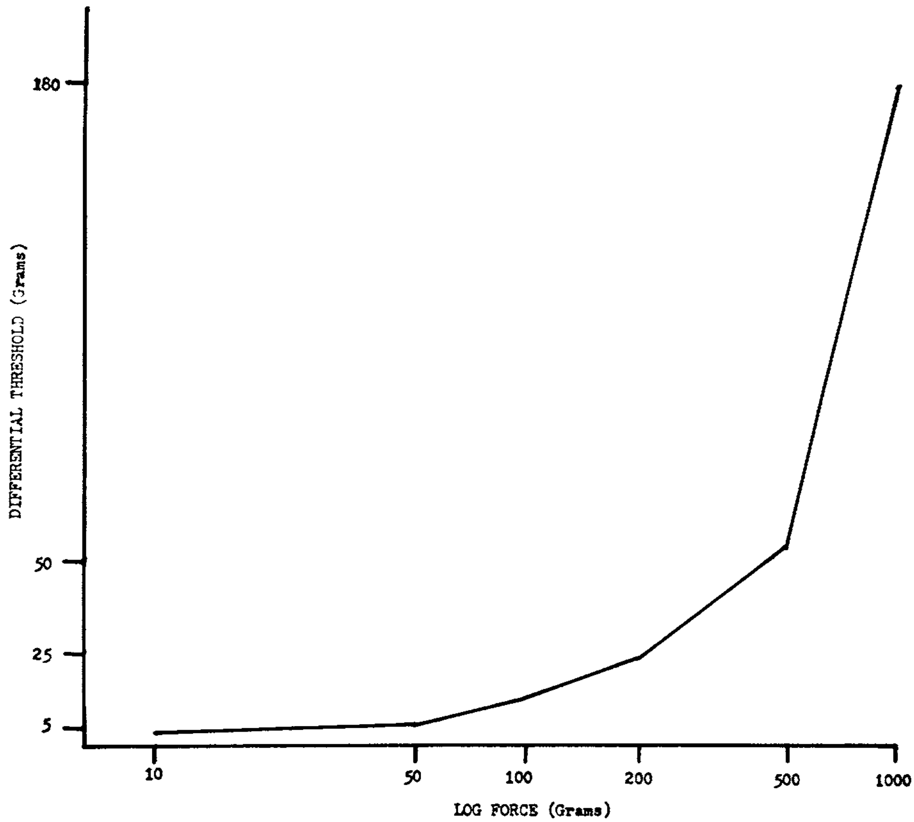

FIG 2.—Mean differential threshold plotted against logarithm of applied force for forces applied to labial surface and directed 90° to the long axis of the crown.

TABLE 4
STATISTICAL COMPARISONS OF X VALUES FROM EQUATION $dS=kI^X$ FOR VARIOUS FORCE APPLICATIONS TO MAXILLARY CENTRAL INCISORS

Comparisons of Force (gm)	t Values: Force Applied on Labial Surface; Directed 90° to Long Axis	t Values: Force Applied on Incisal Surface; Directed Along Long Axis
10 vs 50	17.047‡	18.431‡
10 vs 100	15.899‡	17.773‡
10 vs 200	16.642‡	17.490‡
10 vs 500	16.985‡	18.414‡
10 vs 1,000	12.256‡	14.231‡
50 vs 100	1.951	1.655
50 vs 200	1.743	3.637‡
50 vs 500	2.895†	2.054†
100 vs 200	0.446	1.262
100 vs 500	1.088	0.325
200 vs 500	1.149	1.053
50 vs 1,000	18.529‡	11.034‡
100 vs 1,000	33.260‡	11.532‡
200 vs 1,000	43.400‡	9.183‡
500 vs 1,000	14.412‡	10.638‡

* $0.05 > p > 0.01$. † $0.01 > P > 0.001$. ‡ $P < 0.001$.

sons made between the forces centered around 50, 100, 200, and 500 gm ranged from 0.325 to 3.637, and only the comparisons for 50 versus 200 gm and 50 versus 500 gm showed a statistically significant difference for forces applied along the long axis.

If the X values for the forces centered around 50, 100, 200, and 500 are averaged, the generalized equation for the long axis is $dS = 0.23\ I^{0.861}$ and, for the 90° axis, $dS = 0.24\ I^{0.865}$.

Discussion

The nearly identical discriminatory thresholds and optimal functioning range (50 to 500 gm) obtained for forces applied along the long axis and forces applied on the labial surface and directed 90° to the long axis is of particular interest. These results stand in sharp contrast to the reports of directional

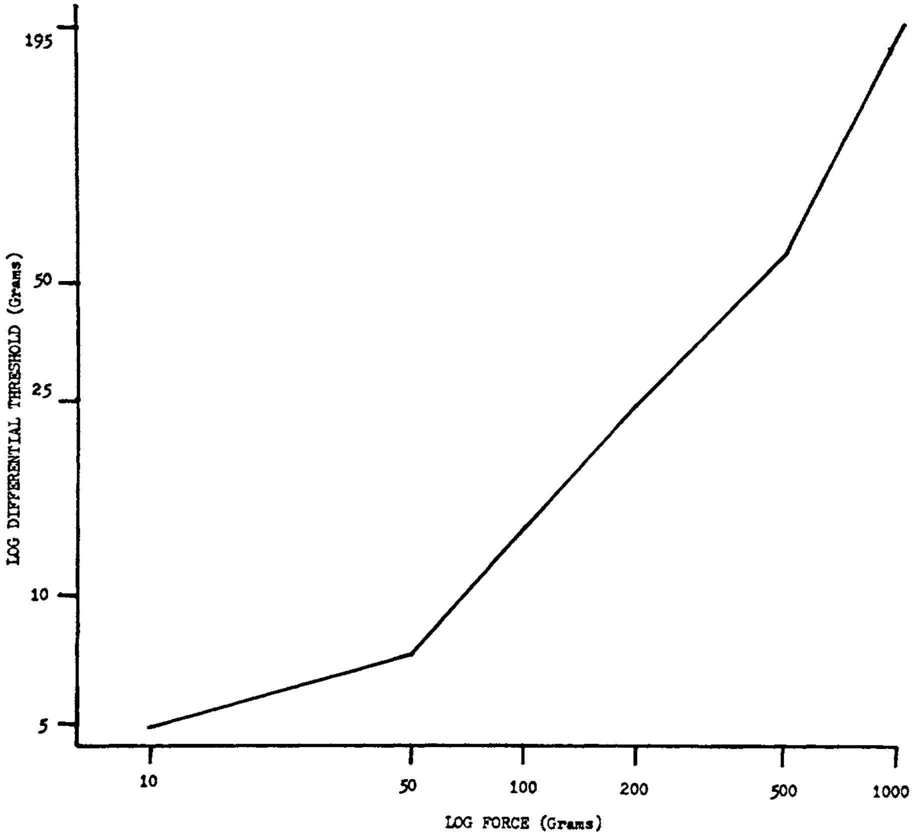

FIG 3.—Logarithm of mean differential threshold plotted against logarithm of applied force for forces applied to incisal surface and directed along the long axis of the crown.

sensitivity in canine teeth of the cat.[3,14] Investigators working with cats have reported that the greatest electrically recorded neural response occurred when the applied force was directed along the long axis of the crown. Moreover, the recorded responses decreased proportionally as the direction of the force was rotated away from the long axis of the crown. This apparent difference may be the result of an actual difference in the functional innervation or of a difference in the anatomical configuration of the two roots. The root of the human maxillary central incisor is nearly straight, and the root of the cat canine is sharply curved.

The Weber ratio values reported in the present study are all higher than the 0.1 value reported by Kawamura and Watanabe.[13] They based differential thresholds on the minimal differences required to make 100% discriminations, however; 70% correct discriminations were required for the present study. Their quantitative assessment of the comparative thicknesses of wires was dependent on more than afferent input originating from the periodontal ligament, which was the situation in the present study, where only direct force application to the tooth was evaluated. In all likelihood, the periodontal ligament receptors served only to apprise the central nervous system that firm contact with the wire had been made by opposing mandibular and maxillary teeth. The actual evaluation would then be an assessment of the placement of the mandible in relation to the skull, determined by the sensory input from the attached muscles or the temporomandibular joint, or both.

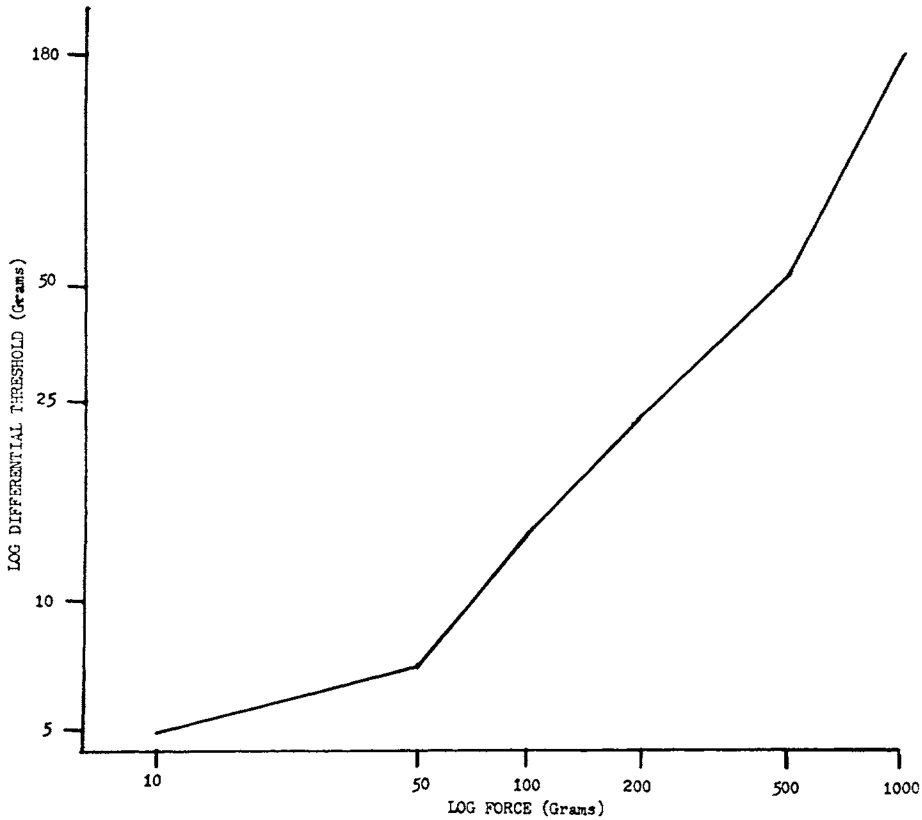

FIG 4.—Logarithm of mean differential threshold plotted against logarithm of applied force for forces applied to labial surface and directed 90° to the long axis of the crown.

Conclusions

The differential thresholds (ie, minimal recognized difference between two forces), centered around force levels of 10, 50, 100, 200, 500 and 1,000 gm. applied to central maxillary incisors, were determined for 50 subjects. The subjects differentiated between these forces most accurately when the applied force ranged from 50 to 500 Gm. The minimal differential between two forces for correct evaluation within this range was 10.5% to 13.8% of the applied force. Forces directed along the long axis of the crown and forces directed 90° to the long axis yielded nearly identical results.

These equations were derived to provide an approximate expression of this phenomenon: $dS=0.23\ I^{0.861}$ for the long axis and $dS=0.24\ I^{0.865}$ for the 90° axis, where I equals the applied force and dS equals the minimal difference in force that can be discerned at this force level.

This quantitative assessment of an individual's ability to evaluate sensory input from the proprioceptors of the periodontal ligament should afford an opportunity to more precisely evaluate changes in proprioception that may result from various dental pathologic changes or dental treatment regimes, or both.

References

1. STEWART, D.: Some Aspects of the Innervation of the Teeth, *Proc Roy Soc* **20**:55-66, 1927.
2. LOEWENSTEIN, W.R., and RATHKAMP, R.: A Study of the Pressoreceptive Sensibility of the Tooth, *J Anat* **71**:232-235, 1936.
3. PFAFFMAN, C.: Afferent Impulses from the Teeth Due to Pressure and Noxious Stimulation, *J Physiol* **97**:207-219, 1939.
4. NESS, A.R.: The Mechanoreceptors of the

Rabbit Mandibular Central Incisor, *J Physiol* **126:**475-493, 1954.

5. KLAFFENBACH, A.D.: Gnathodynamics, *J Amer Dent Assoc* **23:**371-382, 1936.
6. KLATSKY, M.: Masticatory Stresses and their Relation to Dental Caries, *J Dent Res* **21:** 387-390, 1942.
7. WEBER, E.H.: De Pulsu, Resorptione et Tactu Annotation Anatomical et Physiological, *Arch Anat Physiol* **152,** 1834.
8. FECHNER, G.T.: Ueber ein wichtiges Psychophysiches Grundgesetz und dessen Beziehung der Sterngrossen, Abhandl k Ges Wissensch, *Math-Phys Kl* **4:**31-64, 1958.
9. THURSTONE, L.L.: *Psychophysical Analysis: The Measurement of Values,* Chicago: University of Chicago Press, 1959.
10. BORING, E.G.: *History of Experimental Psychology,* ed 2, New York: Appleton-Century Crofts, Inc., 1950, pp 281-294.
11. STEVENS, R.S.: On the Psychophysical Law, *Psychol Rev* **64:**153-181, 1957.
12. TREISMAN, M.: Noise and Weber's Law: The Discrimination of Brightness and Other Dimensions, *Psychol Rev* **71:**314-330, 1964.
13. KAWAMURA, Y., and WATANABE, M.: Studies of Oral Sensory Thresholds: the Discrimination of Small Differences in Thickness of Steel Wires in Persons with Natural and Artificial Dentition, *Med J Osaka Univ* **10:** 291-301, 1960.
14. KRUGER, L., and MICHAEL, F.: A Single Neurone Analysis of Buccal Cavity Representation in the Sensory Trigeminal Complex of the Cat, *Arch Oral Biol* **7:**491-503, 1962.