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The dimensions of the roots of the human permanent dentition as a guide to the selection of optimal orthodontic forces

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Background: The dimensions of the roots of the teeth are important in the assessment of orthodontic anchorage and to estimate the forces to be used during orthodontic tooth movement.
Aims: To investigate the relations between the lengths, widths and projected areas of the roots of the permanent teeth.
Methods: Intact, extracted human permanent teeth were photographed and the lengths, widths and projected areas of selected surfaces measured. Descriptive statistics and associations between selected linear dimensions and root areas were calculated.
Results: The data showed significant kurtosis and skewness. Neither exponential nor polynomial transformations improved the goodness of fit, and there was no a priori reason to use other than linear regression. When the lengths of all teeth were multiplied by the respective widths of the mesial, distal and lingual surfaces, the correlations between the product of length and width and area improved in 28 out of 30 surfaces. In the lower arch the correlation coefficients ranged from $r = .343$ (mesial surface first premolar) to $r = .845$ (mesial surface of the canine). The correlations in the upper arch ranged from $r = .201$ (mesial surface of the second molar) to $r = .847$ (mesial surface lateral incisor).
Conclusions: For clinical purposes, root length may be an acceptable indicator of root area. Low correlations were attributed to variations in root shape.
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Introduction

In 1952 Storey and Smith showed that orthodontic forces above a certain level produced lower rates of tooth movement than forces below that level.[1] They named the lower forces 'optimal' forces. This definition has been extended to include the proviso of little or no permanent damage to the root and/or the tissues surrounding the root. Importantly, it was suggested that it was the pressure exerted by the root on the surrounding tissues rather than the actual numeric value of the force that was a critical factor in tooth movement.[1] Almost coincidentally, Begg published results of cases with dramatically short treatment times treated entirely by using round wires with small cross-sectional areas which seemed to support the notion of differential force, which is the use of light and heavy forces to control the speed of tooth movement.[2]

Various authors have investigated root dimensions such as the surface area;[3–12] root volume,[13,14] the relation between root length and crown diameter[14] and the projected area of the roots,[15,16] that may be important for tooth movement. It has been argued that the relative size of the root(s) may indicate a tooth's resistance to an orthodontic force or the anchorage value.[17] High forces are required to move teeth with large root surface areas. If it were possible to determine the optimal force levels for tooth movement prior to the commencement of treatment, appliances would function with greater efficiency. Our attention was thus focused on the areas of the roots of the permanent dentition.

In this study the lengths, widths and projected areas of the roots of the upper and lower permanent teeth, including the third molars, were measured. Our intention was to gain an insight into the relations

Table I. Upper teeth, lengths and projected areas of selected surfaces.

Surface	Tooth	N	Minimum	Q25	Median	Q75	Maximum	r	R^2
Distal length (cm)	1	32	1.10	1.38	1.50	1.57	1.65	.714	0.511
	2	32	1.36	1.50	1.61	1.68	1.84	.762	0.581
	3	32	1.20	1.56	1.83	1.95	2.05	.838	0.702
	4	30	1.04	1.28	1.39	1.49	1.73	.715	0.512
	5	27	0.98	1.28	1.36	1.46	1.59	.611	0.373
	6	31	0.80	1.13	1.23	1.29	1.54	.524	0.274
	7	32	0.90	1.16	1.27	1.39	1.72	.299	0.090
Distal area (cm^2)	1	32	0.43	0.60	0.65	0.70	0.82		
	2	32	0.56	0.66	0.71	0.77	0.88		
	3	32	0.62	0.82	0.98	1.06	1.54		
	4	30	0.64	0.74	0.83	0.89	1.15		
	5	27	0.48	0.66	0.72	0.77	0.93		
	6	31	1.18	1.47	1.54	1.66	2.08		
	7	32	0.69	1.00	1.12	1.26	1.62		
Lingual length (cm)	1	32	1.08	1.20	1.28	1.37	1.48	.499	0.249
	2	32	1.12	1.20	1.32	1.43	1.59	.731	0.535
	3	32	1.08	1.49	1.66	1.80	1.90	.746	0.557
Lingual area (cm^2)	1	32	0.42	0.45	0.50	0.56	0.70		
	2	32	0.32	0.38	0.45	0.49	0.62		
	3	32	0.34	0.56	0.60	0.64	0.84		
Mesial length (cm)	1	32	1.09	1.41	1.53	1.64	1.74	.803	0.645
	2	32	1.29	1.50	1.59	1.73	1.86	.847	0.717
	3	32	1.20	1.69	1.87	1.99	2.20	.566	0.320
	4	30	1.08	1.29	1.36	1.49	1.71	.713	0.508
	5	27	1.00	1.30	1.39	1.45	1.61	.558	0.312
	6	31	1.06	1.22	1.34	1.41	1.66	.730	0.533
	7	32	1.06	1.20	1.25	1.38	1.62	.201	0.040
	8	12	0.83	0.93	0.99	1.10	1.15	.456	0.208
Mesial area (cm^2)	1	32	0.50	0.59	0.67	0.74	0.85		
	2	32	0.54	0.65	0.69	0.74	0.86		
	3	32	0.61	0.97	1.00	1.09	1.83		
	4	30	0.48	0.73	0.85	0.94	1.13		
	5	27	0.48	0.70	0.74	0.79	0.96		
	6	31	1.10	1.56	1.68	1.81	2.34		
	7	32	0.84	1.14	1.23	1.31	1.75		
	8	12	0.77	0.97	1.19	1.27	1.36		

Table II. Lower teeth, lengths and projected areas of selected surfaces.

Surface	Tooth	N	Minimum	Q25	Median	Q75	Maximum	r	R^2
Distal length	1	30	1.16	1.31	1.39	1.47	1.68	.441	0.195
	2	25	1.20	1.34	1.48	1.57	1.73	.518	0.269
	3	26	1.44	1.61	1.74	1.79	2.17	.835	0.696
	4	39	1.16	1.44	1.50	1.60	2.00	.375	0.141
	5	23	1.21	1.42	1.60	1.64	1.79	.485	0.236
	6	27	0.86	1.19	1.26	1.39	1.70	.608	0.37
	7	27	1.00	1.12	1.20	1.37	1.60	.820	0.672
Distal area	1	30	0.46	0.53	0.57	0.61	0.76		
	2	25	0.48	0.58	0.62	0.68	0.84		
	3	26	0.64	0.80	0.97	1.12	1.51		
	4	39	0.67	0.85	1.02	1.20	1.53		
	5	23	0.64	0.70	0.76	0.80	0.95		
	6	27	0.98	1.30	1.40	1.50	2.24		
	7	27	0.71	1.10	1.30	1.50	1.71		
Lingual length	1	33	1.02	1.18	1.28	1.37	1.65	.529	0.277
	2	47	1.10	1.32	1.40	1.48	1.60	.665	0.442
	3	28	1.36	1.61	1.67	1.77	2.01	.717	0.514
Lingual area	1	33	0.22	0.27	0.29	0.38	0.48		
	2	47	0.26	0.31	0.34	0.37	0.51		
	3	28	0.49	0.61	0.64	0.74	0.93		
Mesial length	1	33	1.31	1.34	1.42	1.51	1.75	.566	0.321
	2	19	1.20	1.45	1.57	1.60	1.78	.594	0.353
	3	22	1.40	1.68	1.78	1.94	2.30	.845	0.714
	4	39	1.16	1.41	1.48	1.56	2.04	.343	0.118
	5	23	1.17	1.45	1.58	1.60	1.84	.582	0.338
	6	27	1.16	1.26	1.40	1.48	1.78	.807	0.651
	7	27	1.02	1.08	1.30	1.41	1.55	.812	0.661
	8	12	1.03	1.28	1.35	1.39	1.73	.554	0.307
Mesial area	1	33	0.53	0.57	0.63	0.67	0.88		
	2	19	0.54	0.60	0.64	0.70	0.92		
	3	22	0.64	0.80	0.96	1.11	1.57		
	4	39	0.66	0.82	1.02	1.15	1.53		
	5	23	0.48	0.70	0.80	0.83	1.06		
	6	27	1.11	1.32	1.46	1.55	2.33		
	7	27	0.87	1.11	1.38	1.50	1.88		
	8	12	0.65	0.70	0.83	1.03	1.50		

between the lengths and widths to the areas of corresponding root surfaces in the hope that this information may be of value to clinicians planning orthodontic anchorage and selecting appropriate forces for tooth movement.

Materials and methods

Measurements were made of the root surfaces of approximately 580 extracted human permanent teeth, including the third molars. Intact and fully formed permanent teeth were collected in the period 1963–65 and measured using the methods described below. The age, gender and ethnicity of the subjects were not recorded.

The teeth were cleaned of attached soft tissue, dried, labelled and numbered. Multi-rooted teeth were sectioned through the furcation(s) in order to obtain a clear view of the root surfaces and each root was photographed and measured separately. The four surfaces of the teeth (mesial, distal, buccal, lingual) were photographed alongside a metric rule. The film plane was parallel to the long axis of each tooth. The photographic images were enlarged x10 and the outline of each root surface traced on paper. The lengths and widths of the roots were measured on the tracings. The length of the proximal surface of a root was the distance from the root apex to the peak of the curve of the cemento-enamel junction on the proximal surface, and the length of a lingual surface was the distance from the apex to the lowest point on the curve of the cemento-enamel junction. Root width was measured at the cemento-enamel junction. The dimensions of the same surfaces were added. Data for corresponding right and left teeth were combined.

The area of each root surface was then measured directly with a planimeter (Allbrit 37595 Fixed Arm planimeter, Stanley, London, UK). The accuracy of the planimeter was tested before use by tracing a circle using the radius arm provided with the instrument to determine if the area of the traced circle coincided with the nominated area. Before analysis, the planimeter measurements were converted to the actual sizes by dividing the linear measurements by 10 and the area measurements by 100. All linear and width measurements are in centimetres (cm) and the areas in centimetres squared (cm^2).

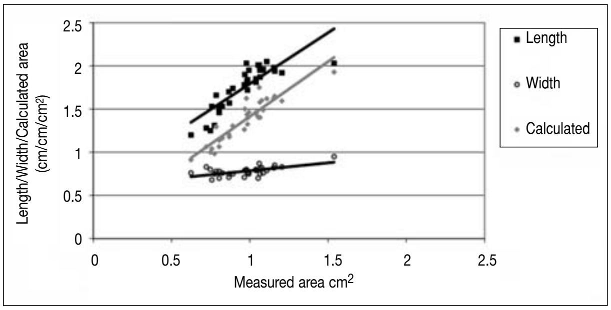
Descriptive statistics and skewness and kurtosis were calculated for the distal, mesial and lingual lengths, widths and projected areas of the upper and lower teeth. Pearson's correlation coefficients and regression equations between the lengths and projected areas of corresponding root surfaces, and associations between root length and the calculated area (the product of length and width) to the projected area of corresponding surfaces were also calculated for teeth with width and length measurements.

Results

The results are given in Tables I and II and Figures 1 and 2. The tables contain the sample sizes, minimum and maximum values, quartile values, medians, correlations of length to the projected areas of selected permanent teeth and coefficients of determination (R^2 values). The measured and calculated values of the various surfaces of selected upper and lower teeth are shown in Figure 1. Regression lines of the relations between projected root length and area of the distal, mesial and lingual surfaces of the upper and lower teeth are given in Figure 2.

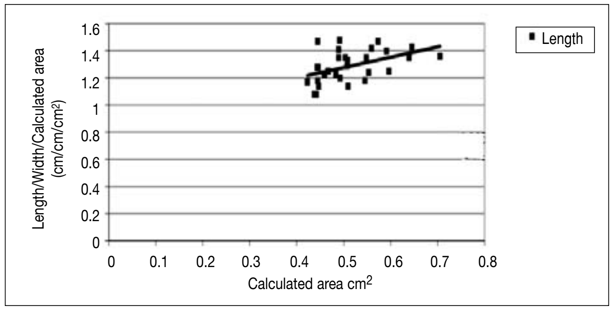
The median length of the distal surface of the upper central incisor root was 1.50 cm and for the upper canine it was 1.83 cm (Table I). The median areas of the distal surfaces of the upper canine and first molar were 0.98 and 1.54 cm^2, respectively. The palatal surface of the upper lateral incisor (Median: 1.32 cm) was slightly longer than that of the upper central incisor (Median: 1.28 cm), but shorter than the upper canine (Median length: 1.66 cm). The median areas of the palatal surfaces of the upper central incisor, upper lateral incisor and upper canine were 0.50, 0.45 and 0.60 cm^2, respectively. Although the mesial surface of the upper first molar was shorter than all other teeth in the upper arch except the second and third molars, it had the largest mesial area (Median: 1.68 cm^2). The mesial areas (medians) of all upper teeth were larger than the distal areas (medians) of corresponding teeth, except for the lateral incisors.

The canine was the longest tooth in the lower arch, but the areas of the mesial and distal root surfaces (Distal surface area median: 0.97 cm^2; Mesial surface area median: 0.96 cm^2) were less than the corresponding areas (Distal area median: 1.40 cm^2; Mesial area median: 1.46 cm^2) of the first molar (Table II). The distal surface of the lower first premolar was shorter than the same surface of the canine, but the median area of the distal surface of the first premolar was greater than the median area of the canine.



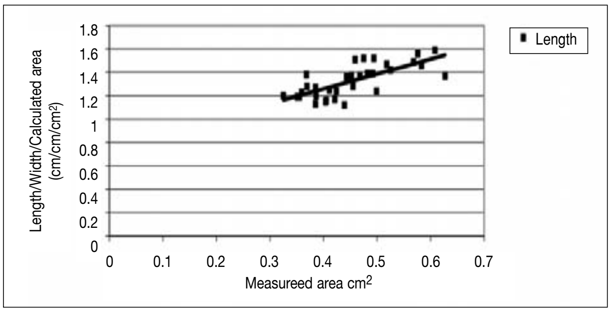
Length: y = 1.1851x + 0.6068 R^2 = 0.7022
Width: y = 0.1838x + 0.6022 R^2 = 0.3644
Calculated area: y = 1.273x + 0.1395 R^2 = 0.8378

(a) Upper canine distal.



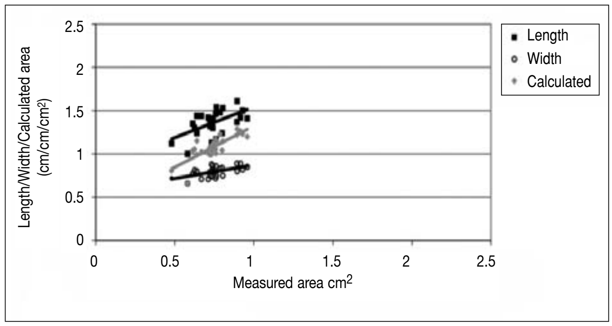
Length: y = 0.7647x + 0.8948 R^2 = 0.2495

(b) Upper central incisor lingual.



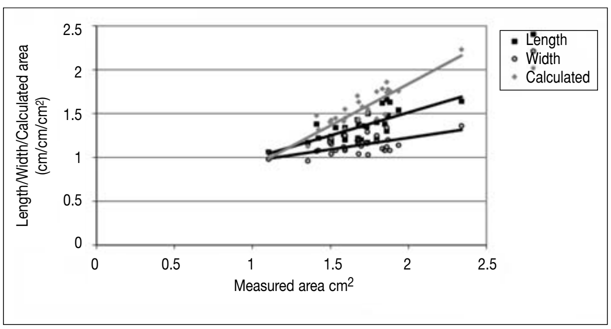
Length: y = 1.2694x + 0.7516 R^2 = 0.5349

(c) Upper lateral incisor lingual.



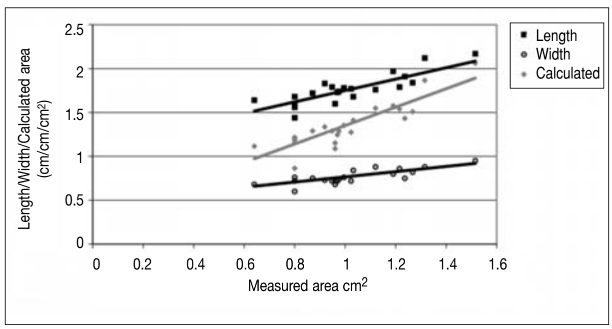
Length: y = 0.7085x + 0.8334 R^2 = 0.3119
Width: y = 0.9536x + 0.369 R^2 = 0.6159
Calculated area: y = 0.3104x + 0.5616 R^2 = 0.3256

(d) Upper second premolar mesial.



Length: y = 0.5239x + 0.465 R^2 = 0.533
Width: y = 0.2651x + 0.6938 R^2 = 0.3841
Calculated: y = 0.9501x + 0.0614 R^2 = 0.7864

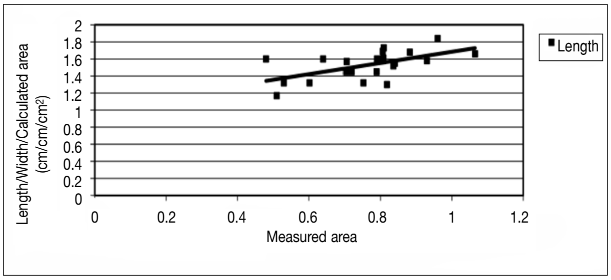
(e) Upper first molar mesial.



Length: y = 0.6499x + 1.1004 R^2 = 0.6968
Width: y = 0.2969x + 0.4695 R^2 = 0.6301
Calculated: y = 1.0502x + 0.3006 R^2 = 0.7814

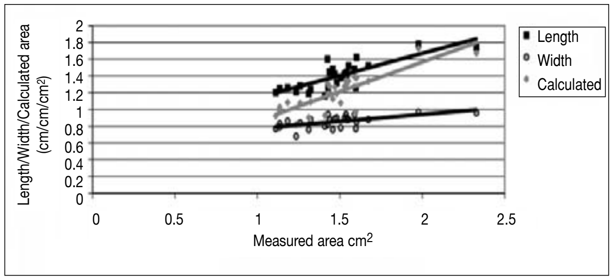
(f) Lower canine distal.

Figure 1. Plots derived from raw data. Individual data are indicated and regression lines for length, width and calculated area (length x width) with the projected (measured) area are given.



Length: y = 0.657x + 1.0277 R^2 = 0.3383

(g) Lower second premolar mesial.



Length: y = 0.52181x + 0.6131 R^2 = 0.6509
Width: y = 0.1664x + 0.6087 R^2 = 0.3484
Calculated: y = 0.7048x + 0.1559 R^2 = 0.6835

(h) Lower first molar mesial.

Figure 1 (Continued). Plots derived from raw data. Individual data are indicated and regression lines for length, width and calculated area (length x width) with the projected area are given.

In the upper arch, the coefficients range from .847 between the length and area of the mesial surface of the lateral incisor to .201 between the length and area of the mesial surface of the second molar. The correlation coefficient between the distal surface and distal area of the upper canine was .838 and between the length and area of the mesial facing root surfaces of the upper first molar it was .730. In the lower arch, the coefficients for the distal surface of the canine and the mesial surface of the first molar were .835 and .807, respectively.

There was significant kurtosis and skewness in the data (more than two standard deviations) indicating that the distributions were not normal, but there was no apparent relationship between skewness and the coefficients of determination, nor was there any consistency in the sense or direction of the skew. However, neither exponential nor polynomial transformations improved the goodness of fit, and there is no a priori reason to use other than linear regression. Coefficients of determination (R^2) for selected teeth are given in Tables I and II. The coefficient of determination indicates the degree to which the variation amongst projected areas can be accounted for by root length.

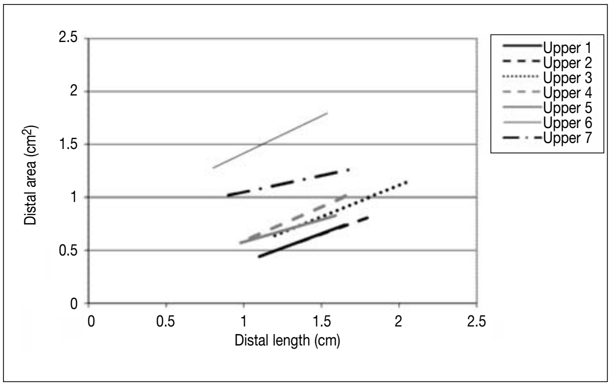
When the lengths of the upper teeth were multiplied by the respective widths the correlations with the corresponding root surface lengths increased in 28 of 30 surfaces. Only the correlations between the lengths and calculated areas of the distal surfaces of the upper first and second molars, and the mesial lengths and calculated areas of the lower lateral incisor and distal surface of the lower central incisor did not improve.

Discussion

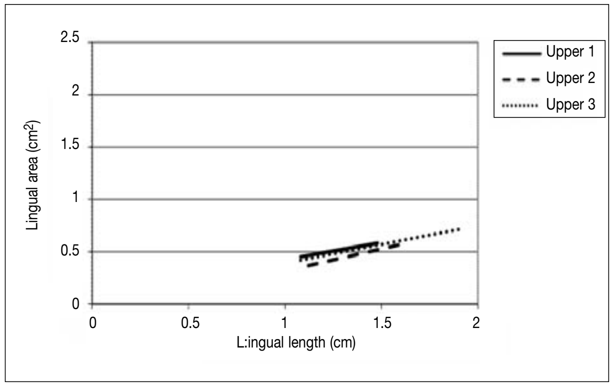
This study set out to determine if clinically useful associations existed between the lengths and areas of the roots of the upper and lower teeth, however later in the study, root width was included to determine whether that dimension was of any value in estimating projected area. A strong association (>.8) would enable a clinician to use the product of root length and width as a predictor of root area and select an appropriate force to obtain optimal tooth movement and/or estimate the anchorage value of a tooth or group of teeth.

The coefficients for the distal surfaces of the upper canines and the mesial surfaces of the lower first molars accounted for approximately 70 and 65 per cent of the variations in root area, respectively, when the root lengths were known. The coefficients of determination were relatively high for several other teeth, notably the mesial surfaces of the upper lateral incisor and the lower first and second molars. The coefficient of determination for the lingual surface of the upper central incisor was only .249, possibly because an incisor with a short, wide root can have the same area as one with a long, slender root. For the upper central incisor, root length alone is not a good predictor of root area. We succeeded in improving the predictability of root length by using a calculated area (length x width) in our calculations. Data for these calculations are available on the Journal website. In all but two cases, this quantity accounted for more variance than using length alone.

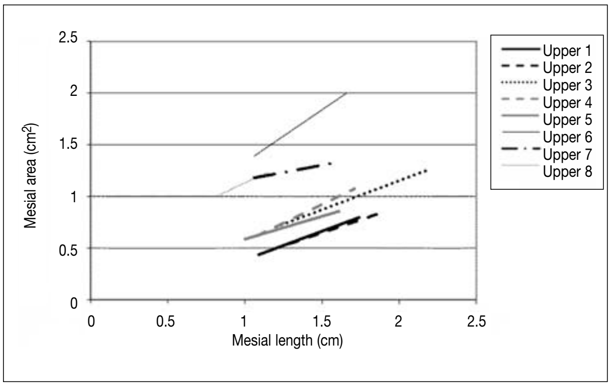
Estimation of optimal forces needs to take into account teeth with unusual variations in the axes of



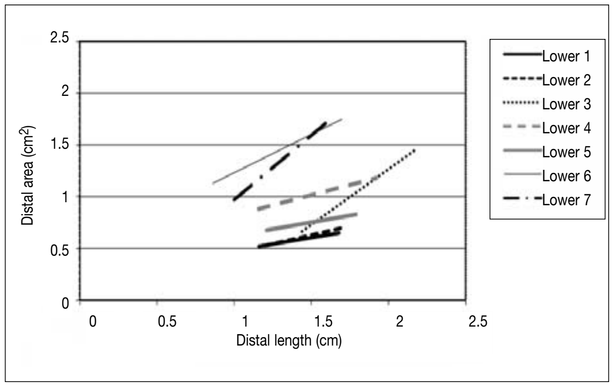
(a) Regression lines showing the relations between distal lengths and areas for the upper teeth.



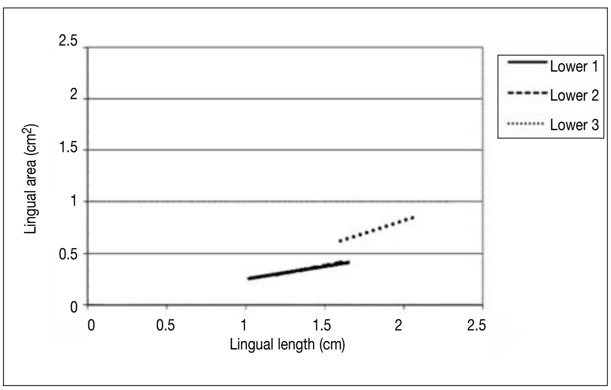
(b) Lingual lengths and areas for the upper teeth.



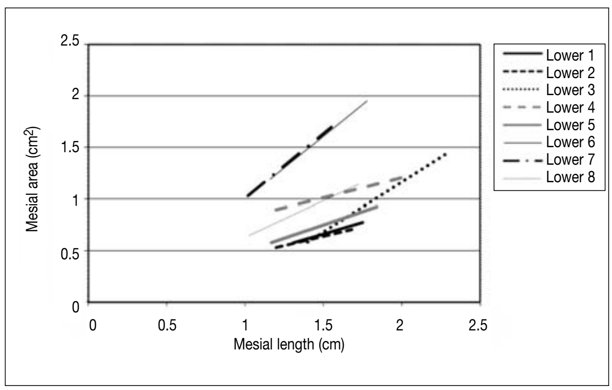
(c) Mesial lengths and areas for the upper teeth.



(d) Distal lengths and areas for the lower teeth.



(e) Lingual lengths and areas for the lower teeth.



(f) Mesial lengths and areas for the lower teeth.

Figure 2. Regression lines for the length and areas of the upper and lower teeth.

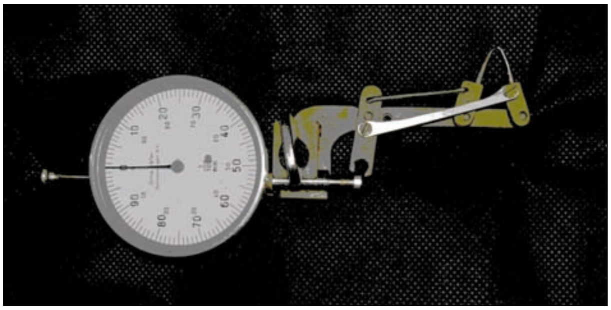


Figure 3. Caliper designed to measure tooth dimensions at the cemento-enamel junction.

the crowns and roots and/or root bends or curves.[18,19] Also the shape of the cemento-enamel junction on a proximal surface varies according to the labio-lingual width of the root.[18] In a wide tooth the curve of the cemento-enamel junction has a somewhat flattened shape, whereas in a narrow tooth the junction is somewhat angular in shape.

Limitations in this study that should be considered are our methods of measuring length and area: both measurements were made parallel to the long axis of the root and were influenced to a certain degree by the angle between the root surface and the long axis of the tooth, and the shape of the root. Some teeth had pyramidal roots and other teeth had curved roots. These variations, although small, may contribute to the variability in tooth movement encountered by a clinician using root length to estimate root area and an optimal force. For some teeth the projected length, for example of the upper lateral incisor, would be less than the actual length. When, however, the width (at right angles to the root surface of interest) and the projected length of a root are known, the actual length of the root can be calculated. Bucco-lingual widths are difficult to measure using traditional radiographs. To overcome this, we designed a caliper to measure the width at the cemento-enamel junction and have used this instrument to estimate projected areas and have obtained results consistent with other workers (Figure 3).[16,20,21] Finally, the strengths of this study are the size of the samples and our use of teeth with fully developed roots.

How can the results be applied to estimate the optimum force for tooth movement or anchorage? To use the graphs, first decide on a treatment plan and the directions of tooth movement. Estimate the root length of a particular tooth from a radiograph or from an already extracted tooth and use the appropriate regression line to obtain an estimate of root area. As the mean peak velocity of movement of the canines in both humans and dogs occurred when a mean pressure of 200 cN/cm^{-2} was exerted, multiply this estimated area by 200 (as force equals pressure x area) to determine the force required.[20] When this figure is applied to the median projected area of the distal surface of the upper canine (0.98 cm^2) the mean optimum pressure is 196 cN/cm^{-2}. This approximates reported estimates of 197 cN/cm^{-2} based on experimental data from humans.[1,16,21,22] Using this approach it is now possible to estimate the forces required to obtain optimal rates of tooth movement and, by using higher forces, a stable anchor unit. Eventually, other root dimensions, such as volume and bone density may improve estimates of a tooth's resistance to orthodontic movement than either root length or the product of root length and width.[12,13]

Conclusions

The following conclusions were drawn:

1. For clinical purposes, root length may be an acceptable indicator of root area.

2. The product of root length and width resulted in higher coefficients of determination. A method of measuring bucco-lingual width is described.

2. Low correlations between root length and area were attributed to variations in root shape.

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References

1. Storey E, Smith R. Force in orthodontics and its relation to tooth movement. Aust J Dent 1952;56:11–18.
2. Begg PR. Stone age man's dentition. Am J Orthod 1954;40: 517–31.
3. Brown R. A method of measurement of root area. J Can Dent Assoc 1950;16:130–2.
4. Jepsen A. Root surface measurement and a method for x-ray determination of root surface area. Acta Odontol Scand 1963:21:35–46.
5. Hillam DG. Stresses in the periodontal ligament. J Periodont Res 1973; 8:51–6.
6. Nicholls JI, Daly CH, Kydd WL. Root surface measurement using a digital computer. J Dent Res 1974;53:1338–41.
7. Jarabak JR, Fizzell JA. Techniques and treatment with the light wire appliances: light differential force in clinical orthodontics. Mosby, St Louis 1963:192–3,353–79.
8. Herman DW, Gher ME Jr, Dunlap RM, Pelleu GB Jr. The potential attachment area of the maxillary first molar. J Periodontol 1983;54:431–4.
9. Anderson RW, McGarrah HE, Lamb RD, Eick JD. Root surface measurements of mandibular molars using stereo-photogrammetry. J Am Dent Assoc 1983:107:613–15.
10. Dunlap RM, Gher ME Jr. Root surface measurements of the mandibular first molar. J Periodontol 1985;56:234–8.
11. Verdonshot EH, Sanders AJ, Plasschaert AJ. Computer-aided image analysis system for area measurement of tooth root surfaces. J Periodontol 1990; 61:275–80.
12. Mowry JK, Ching MG, Orjansen MD, Cobb CM, Friesen LR, MacNeill SR et al. Root surface area of the mandibular cuspid and bicuspids. J Periodontol 2002;68:1095–100.
13. Bjorndal AM, Henderson WG, Skidmore AE, Kellner FH. Anatomic measurements of human teeth extracted from males between the ages of 17 and 21 years. Oral Surg 1974; 38:791–803.
14. Kay S, Forscher BK, Sackettt LM, Tooth root length-volume relationships, an aid to periodontal prognosis. 1. Anterior teeth. Oral Surg Oral Med Oral Pathol 1954:7:735–40.
15. Garn SM, Van Alstine WL Jr, Cole PE. Relationship between root lengths and crown diameters of corresponding teeth. J Dent Res 1978;57:636.
16. Lee BW. The force requirements for tooth movement. Part III: The pressure hypothesis tested. Aust Orthod J 1996;14: 93–7.
17. Chen SK, Pan JH, C CM, Jeng JY. Accuracy of supported root ratio estimation from projected length and area using digital radiographs. J Periodontol 2004;75:866–71.
18. Taylor RMS. Variation in form of human teeth: I. An anthropologic and forensic study of maxillary incisors. J Dent Res 1969; 48:5–16.
19. Taylor RMS. Variation in form of human teeth: I. An anthropologic and forensic study of maxillary canines. J Dent Res 1969; 48:173–82.
20. Ren Y, Maltha J, Van't Hof MA, Kuijpers-Jagtman AM. Optimum force magnitude for orthodontic tooth movement: a systematic literature review. Am J Orthod Dentofacial Orthop 2004;125:71–7.
21. Lee BW. The force requirements for tooth movement. Part I: Tipping and bodily movement. Aust Orthod J 1995;13: 238–48.
22. Smith R, Storey E. The importance of force in orthodontics. Design of cuspid retraction springs. Aust J Dent 1952;56: 291–304.