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Original Article

Properties of manual toothbrush that influence on plaque removal of interproximal surface *in vitro*

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KEYWORDS
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Abstract *Background/purpose:* Few papers were available on the interproximal cleaning efficiency by manual toothbrushes when used alone. The aim was to investigate the efficiency of commercially available toothbrushes on interproximal cleaning and determine the key properties that would make the differences.
Materials and methods: Artificial-teeth were coated with manicure type experimental dental plaque covering mainly the interproximal surface and fixed in the jaw model of a dental simulator. A modified scrubbing technique was employed to brush out the plaque conducted by one trained dentist using 26 different toothbrushes from the equal number of separate interproximal conditions. The rate of the plaque removal (%) was calculated by measuring the plaque free areas on the post-brush images.
Results: The data analysis using mixed effect modelling showed that stiffness, number of tufts and total length have effect on the rate of the plaque removable from the interproximal surfaces.
Conclusion: This study indicated consideration should be given to toothbrush properties to enhance plaque removal from the interproximal surfaces.

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Introduction

Dental caries is mainly dental plaque-dependent oral infectious disease.[1,2] Elimination of dental plaque that contains cariogenic pathogens is considered to be essential for caries prevention and management. Daily plaque control is definitely important for caries prevention.[3] Manual toothbrush appears to be the most widely used tool in home care for plaque control. Manufactures have been made an effort to achieve effective plaque removal by improving the design of manual toothbrush. A wide variety of the manual toothbrushes are commercially available. However, the recent information and study of manual toothbrush alone is limited.[4–7]

Dental plaque tends to more highly accumulate on the interproximal surface than smooth or occlusal surface. Therefore, attention should be paid precisely more than another surfaces when brush the teeth. This is why that regular usage of dental floss, interdental brush and tooth pick are recommended. Several studies investigated the plaque removal efficiency in combination with tooth brush and dental floss or interdental brush.[8–13] However, these cleaning tools still not commonly used.[14] One of the goals of oral health in Health Japan 21, in which the Japanese government clarified its health policy, is 50% or more of Japanese adults to ensure the use of cleaning tools for interproximal surface.[15] National Health and Nutrition Survey are also reported that the frequency of use of dental floss or interdental brushes among Japanese adults was under 30%.[16] Therefore, plaque removal efficiency by manual toothbrush alone is indispensable for the dental caries prevention.

The aim of this study was to evaluate the interproximal cleaning efficiency of the commercially available manual toothbrushes when used alone. In addition, we tried to find out the properties of manual toothbrush that effect on the interproximal cleaning.

Materials and methods

Tested toothbrushes and their properties

Twenty-six commercially available toothbrushes were selected from the Japanese market in 2018. The nine properties of these toothbrushes: bristle stiffness (soft, semi-soft, medium and hard model), length of bristle, head area, bristle area, number of tufts, diameter of bristle, form of brush (sharp, dome and flat), step (with and without) and total length were listed in Table 1.

In Japan, the Household Goods Quality Labeling Act sets out what must be displayed regarding the quality of goods by the manufacturers and how they should be displayed material, the bristle stiffness and heat-resistant temperature are needed to display for toothbrush (see Table 2). Especially, the bristle stiffness divided into three classes: hard is over 75 N/m^2, normal is between 50 and 85 N/m^2 and soft is under 60 N/m^2 by the bristle stiffness test based on Japanese Industrial Standards (JIS S3016). Length of bristle and head area and bristle area were directly measured. Form of a brush (sharp, dome and flat) and step (with and without) were clearly different from each other in shape.

Experimental plaque model

The experiment used in this study is shown in Fig. 1. In brief, artificial-tooth of mandibular left first molar was removed from the jaw model of a dental simulator (D18FE-500E, Nissin Dental Products INC., Kyoto, Japan) and its interproximal surface was coated with a manicure type experimental dental plaque (Artificial Plaque, Nissin Dental Products INC., Kyoto, Japan). Then, the coated artificial-tooth was carefully reset to the jaw model and the model was mounted into the dental simulator before using the brushes.

Brushing test with toothbrushes

Brushing test was conducted by one trained dentist. The bristles were placed at 90° angle to the artificial-tooth according to scrubbing method. The brush was conducted with a horizon brushing motion (stroke: 10 mm) on buccal and lingual of mandibular left first molar artificial-tooth at 30 strokes/15 seconds on each side. The brushing pressure was controlled between 134.6 and 196.1 g. Five experiments were randomly performed for each toothbrush.

Measurement of plaque removal area

After brushing, the artificial-tooth was removed from the jaw model and mounted in mold. In order to record and measure the plaque removal area, photographs were taken by digital single-lens reflex camera for dental use (Nikon D100, Sunphoto, Saitama, Japan). The exposure time and ISO were set as 1/125 second and 200. The captured images were analyzed using Adobe photoshop CS5 Extended (Adobe Systems Incorporated, San Jose, USA). The area of plaque removal as evaluated by the number of pixels in each image was measured. Subsequently, the rate of plaque removal was analyzed using the pixel counts of these images and was calculated by following formula: Plaque removal rate (PRR, %) $=$ non-coated area after brushing/coated area before brushing $\times$ 100.

Table 1 Commercially available toothbrushes used in this study.

Product	A	B	C	D	E	F	G	H	I	J	K	L
PRR (%) mean ± SD	48.4 ± 8.2	47.6 ± 7.3	47.4 ± 7.5	44.4 ± 16.2	44.3 ± 7.5	44.0 ± 4.7	42.5 ± 1.5	42.3 ± 8.3	40.6 ± 7.6	39.5 ± 8.8	39.4 ± 5.4	39.1 ± 12.6
Bristle stiffness	Normal	Normal	Soft	Normal	Normal	Normal	Normal	Normal	Normal	Soft	Normal	Soft
Length of bristle (mm)	9.0	9.5	10.5	11.5	12.0	8.5	9.5	9.0	10.0	9.0	10.5	9.0
Head area (mm^2)	270.0	208.0	200.0	364.6	178.5	270.0	210.0	270.0	181.7	230.0	200.0	270.0
Bristle area (mm^2)	140.0	120.0	120.0	243.8	105.6	140.0	144.5	140.0	134.0	150.0	120.0	140.0
Number of tufts	24	23	24	34	17	24	24	24	22	30	24	24
Diameter of bristle (mm)	0.17	0.20	0.14	0.13	0.17	0.19	0.14	0.19	0.17	0.15	0.19	0.15
Form of brush	Flat	Flat	Dome	Sharp	Sharp	Flat	Flat	Flat	Flat	Flat	Dome	Flat
Bristling step	Without	Without	Without	With	Without	Without	With	Without	With	Without	Without	Without
Total Length (mm)	169.0	179.0	180.0	195.0	170.0	169.0	168.0	169.0	181.0	178.0	180.0	169.0

Plaque removal rate was abbreviated as PRR. Standard Deviation was abbreviated as SD.

Statistics

We used a mixed effect modeling and the simulations were carried out by the statistically significant factors for the PRR. The statistical methods used for the simulation model were mixed effect modeling and neural network.[17–21]

Fixed effect model and random effect model were specified by following formula.

$$-\text{L1}: PPR_{ij} = \pi_{0j} + \sum_{m=1}^{9} \pi_{1j}^{(m)}(\text{Facotors indexed by } m)_{ij} + e_{ij} \qquad [1]$$

Table 2 Descriptive analysis of the 9 properties of the manual toothbrush that effects on the plaque removal.

		n	PRR (%)	SD			n	PRR (%)	SD			n	PRR (%)	SD
Bristle	Soft	55	33.9	9.0	Bristle	105.6	5	44.3	7.5	Diameter	0.10	5	34.5	2.1
stiffness	Semi-soft	10	38.0	10.7	area (mm^2)	119.0	5	22.7	6.0	of bristle	0.11	15	32.2	6.1
	Normal	60	39.5	11.4		120.0	20	41.1	9.6	(mm)	0.13	5	44.4	16.2
	Hard	5	22.7	6.0		123.8	5	22.2	2.9		0.14	20	37.0	10.9
Length of	8.5	10	33.1	12.0		134.0	5	40.6	7.6		0.15	20	36.5	8.7
bristle (mm)	9.0	20	42.3	9.6		140.0	30	39.2	10.1		0.16	5	32.3	3.4
	9.5	15	40.0	9.2		144.5	20	36.1	4.8		0.17	40	33.8	13.3
	10.0	10	37.6	7.7		150.0	5	39.5	8.8		0.19	15	41.9	6.2
	10.5	15	40.4	7.5		199.5	5	33.2	11.1		0.20	5	47.6	7.3
	10.8	5	27.5	3.1		228.0	5	27.5	3.1	Form	Flat	75	37.2	10.2
	11.0	15	31.4	4.7		232.8	5	36.0	7.0	of brush	Dome	10	43.4	7.5
	11.5	10	41.5	15.4		243.8	5	44.4	16.2		Sharp	45	33.4	11.6
	12.0	20	28.9	13.3		268.8	5	15.6	5.7	Bristling	Without	85	35.6	11.8
	12.5	5	37.4	3.3		271.3	10	38.0	10.7	step	With	45	37.9	8.6
	13.4	5	36.0	7.0	Number	17	10	33.5	13.1	Total	162.0	5	22.2	2.9
Head	178.5	5	44.3	7.5	of tufts	22	10	31.4	11.1	Length (mm)	168.0	20	36.1	4.8
area (mm^2)	181.7	5	40.6	7.6		23	10	38.7	11.2		169.0	30	39.2	10.1
	190.0	5	22.2	2.9		24	60	38.9	8.5		170.0	10	33.5	13.1
	200.0	10	43.4	7.5		30	5	39.5	8.8		178.0	5	39.5	8.8
	204.3	5	22.7	6.0		34	5	44.4	16.2		179.0	10	38.7	11.2
	208.0	10	38.7	11.2		37	5	33.2	11.1		180.0	10	43.4	7.5
	210.0	20	36.1	4.8		38	15	37.3	9.4		181.0	5	40.6	7.6
	230.0	5	39.5	8.8		39	5	27.5	3.1		183.0	5	27.5	3.1
	270.0	30	39.2	10.1		48	5	15.6	5.7		190.0	20	31.2	13.3
	305.0	5	33.2	11.1	Repeat	1	26	35.7	11.4		192.0	5	36.0	7.0
	318.6	5	27.5	3.1		2	26	38.6	11.7		195.0	5	44.4	16.2
	353.8	5	36.0	7.0		3	26	34.8	10.0					
	364.6	5	44.4	16.2		4	26	39.1	11.7					
	375.2	10	38.0	10.7		5	26	33.7	8.7					
	414.5	5	15.6	5.7										

Plaque removal rate was abbreviated as PRR. Standard Deviation was abbreviated as SD.

M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
38.5 ± 15.7	37.4 ± 3.3	36.0 ± 7.0	35.1 ± 3.9	34.7 ± 7.4	34.5 ± 2.1	33.2 ± 11.1	32.3 ± 3.4	29.9 ± 5.9	27.5 ± 3.1	26.7 ± 2.1	22.7 ± 6.0	22.2 ± 2.9	15.6 ± 5.7
Semi-soft	Semi-soft	Soft	Soft	Soft	Soft	Normal	Normal	Soft	Soft	Soft	Hard	Soft	Normal
11.5	12.5	13.4	10.5	10.0	11.0	12.0	11.0	9.5	10.8	11.0	12.0	8.5	12.0
375.2	375.2	353.8	210.0	270.0	210.0	305.0	210.0	208.0	318.6	270.0	204.3	190.0	414.5
271.3	271.3	232.8	144.5	140.0	144.5	199.5	144.5	120.0	228.0	140.0	119.0	123.8	268.8
38	38	38	24	24	24	37	24	23	39	24	17	22	48
0.17	0.15	0.14	0.10	0.11	0.11	0.17	0.16	0.15	0.17	0.11	0.17	0.14	0.17
Flat	Sharp	Sharp	Flat	Flat	Sharp	Sharp	Sharp	Flat	Flat	Flat	Sharp	Flat	Sharp
With	With	With	With	Without	With	Without	With	Without	Without	Without	Without	Without	Without
190.0	190.0	192.0	168.0	169.0	168.0	190.0	168.0	179.0	183.0	169.0	170.0	162.0	190.0

$$-\mathrm{L2}:\pi_{0j}=\beta_{0j}+\gamma_{0j}+\sum_{n=1}^{26}\beta_j^{(n)}(\text{Tooth brush indexed by } n)_{ij}+\sum_{n=1}^{26}\beta\gamma_j^{(n)}(\text{Tooth brush indexed by } n)_{ij}+r_{ij} \quad [2]$$

a) b)

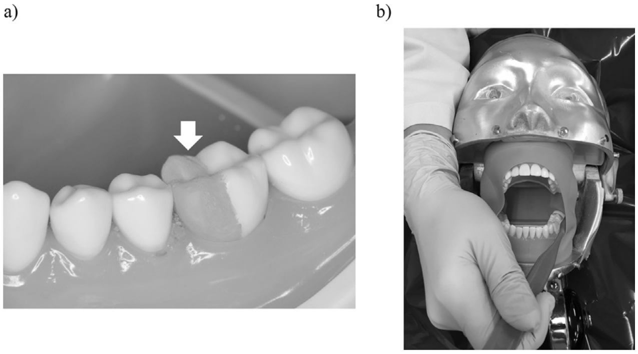

Figure 1 Experimental setting up for plaque removal by toothbrush. a) Artificial plaque before brushing is indicated by white arrow. b) Arrangement of the toothbrush to artificial tooth in the jaw model of a dental simulator.

where $e_{ij} \backsim N(0,\sigma_e^2), and r_{ij} \backsim N(0,\sigma_r^2)$ [3]

These procedures were carried out by SPSS statistics ver 22.0 and IBM SPSS Modeler ver 17.0 (IBM, Tokyo, Japan).

Results

Representative photographs in the interproximal views before and after the test are shown in Fig. 2. Experimental dental plaque was not sufficiently removed, especially in contact area. The mean value of all PPR was 36.4 ± 10.8%. Highest PRR was obtained by the product A (48.4 ± 8.2%), which normal bristle stiffness, length of bristle: 9.0 mm, head area: 270.0 mm^2, bristle area: 140.0 mm^2, number of tufts: 24, diameter of bristle: 0.17 mm, flat form of brush, no step and total length: 169.0 mm. On the other hand, lowest PRR was obtained by the product Z (15.6 ± 5.7%), which were normal bristle stiffness, length of bristle: 12.0 mm, head area: 414.5 mm^2, bristle area: 268.8 mm^2, number of tufts: 48, diameter of bristle: 0.17 mm, sharp form of brush, no step and total length: 190.0 mm.

We applied mixed effect modeling with repeated measures. By the fixed effect model, stiffness, number of tufts and total length may have effect on the PRR. Then random

a) b) c)

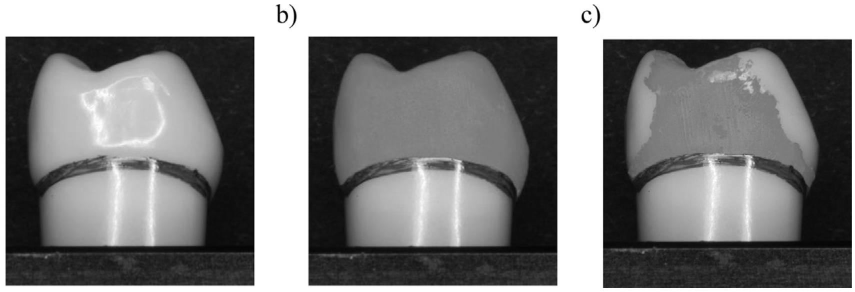

Figure 2 Interproximal views of the lower left first molar in artificial-tooth. a) Before coating with artificial plaque (test surface). b) Coated with artificial plaque before brushing. c) After brushing.

Table 3 Mixed effect modeling results for 9 properties of the manual toothbrush that effects on the plaque removal.

		Model A				Model B			
		Coefficient	fixed effect		*p* Value	Coefficient	fixed effect		*p* Value
			Lower	Upper			Lower	Upper	
Intercept		−0.169	−0.650	0.313	0.489	−0.089	−0.699	0.520	0.773
Bristle stiffness	Soft	Reference				Reference			
	Semi-soft	0.032	−0.082	0.146	0.577	0.079	−0.020	0.178	0.118
	Normal	−0.162	−0.282	−0.043	0.008	−0.192	−0.320	−0.065	0.003
	Hard	0.019	−0.039	0.076	0.523	0.049	−0.001	0.099	0.056
Length of bristle		−0.013	−0.039	0.013	0.327				
Head area		0.001	<0.001	0.001	0.170				
Bristle area		−0.001	−0.003	0.002	0.642				
Number of tufts		−0.01	−0.021	<0.001	0.055	−0.01	−0.015	−0.005	<0.001
Diameter of bristle		0.675	−0.456	1.806	0.239				
Form of brush	Sharp	Reference							
	Dome	0.053	−0.028	0.134	0.196				
	Flat	0.002	−0.059	0.063	0.944				
Bristling step	With	Reference							
	Without	−0.054	−0.122	0.013	0.114				
Total length		0.005	0.001	0.008	0.008	0.004	0.001	0.008	0.05
AIC		−170.032				−220.14			
BIC		−156.221				−203.936			

Akaike's Information Criterion was abbreviated as AIC. Bayesian Information Criterion was abbreviated as BIC.
Model A: Fixed effect model by all variables used in this study.
Model B: Random intercept and random slope model variables were selected by the p values of model A.
AIC and BIC were clearly decreased in Model B compared with Model A.

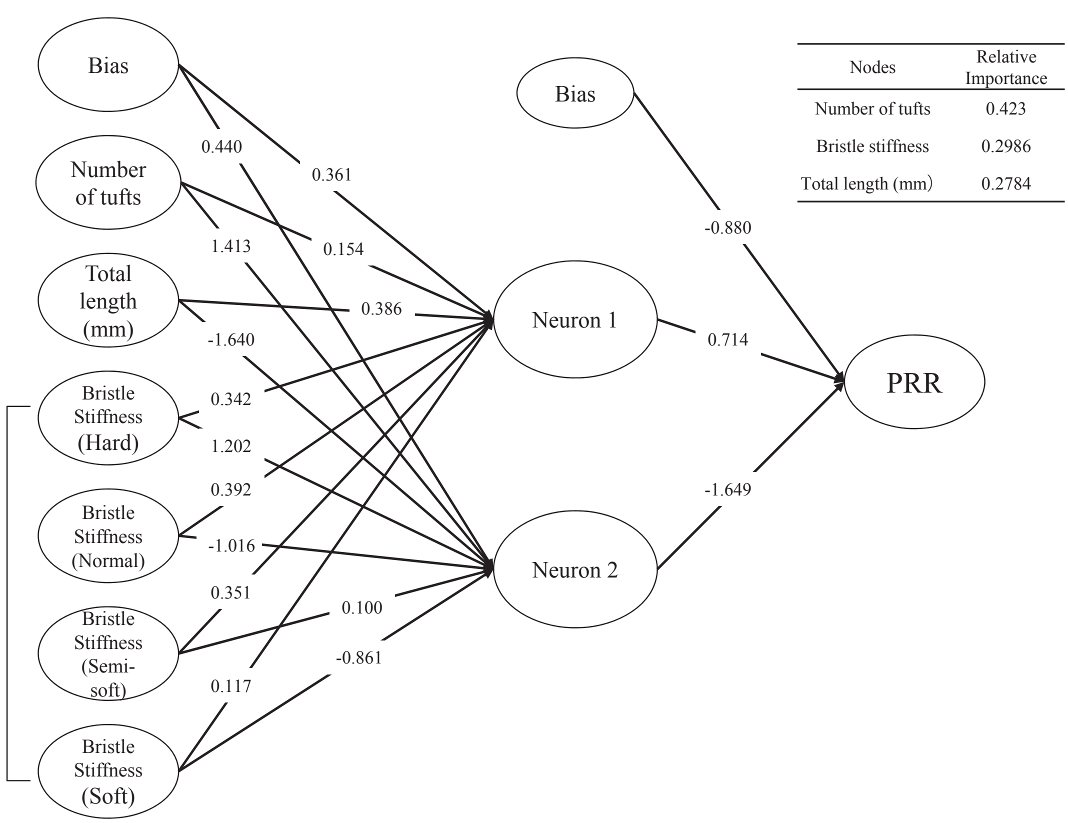

Figure 3 Predictive value of PRR% of the neural network model.

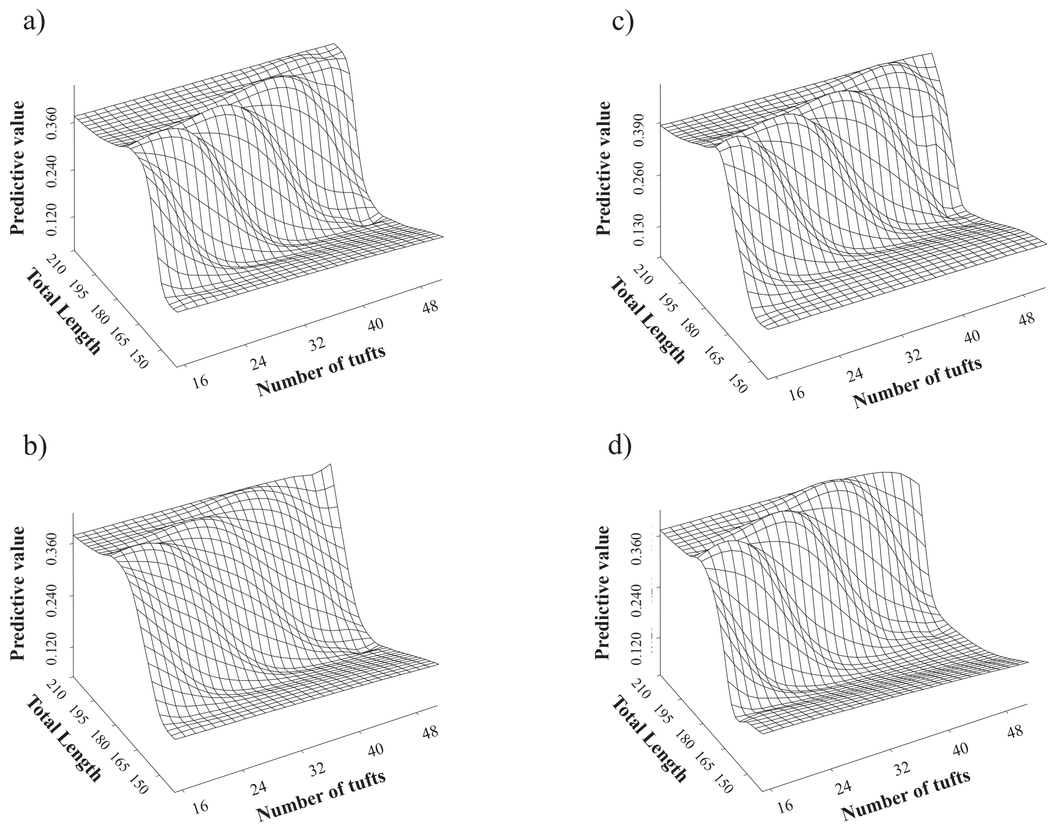

Figure 4 Response surface for multi factor effect on stiffness, number of tufts and total length. a) Soft type toothbrush b) Semi-soft type toothbrush. c) Normal type toothbrush. d) Hard type toothbrush.

effect models with random intercept and random slope were constructed by these three properties. When compared by the fitness indexes index (AIC and BIC), suitable model was obtained by the random intercept model. Normal type model toothbrush was more effective than other hard or soft type model toothbrush. Small tufts type was more effective. And long handle type was more effective (Table 3).

Then, we constructed prediction model for the PRR by these three properties: stiffness, number of tufts and total length. We constructed mixed effect modeling model with repeated measurements and neural network model. The neural network model was illustrated in Fig. 3. By the residual analysis, the accuracy of these two models was almost same but that of neural network model was slightly higher than that of mixed effect modeling. When evaluated by scatter plot and correlation for mixed effect modeling r was 0.525 and for neural network model r was 0.619 respectively.

Finally, we calculated predictive value of PRR by the neural network model. As the stiffness of the brush is a categorical variable, the response surfaces were calculated separately by the soft type, semi-soft type, normal type and hard type model toothbrush. The response surfaces were portrayed in Fig. 4. The predictive value of PRR was linearly increased with the total length from 165.0 mm to 195.0 mm. Over the total length 195.0 mm, the predictive value of PRR becomes flat. Three waves were observed by the combination of number of tufts and total length for each stiffness model.

Discussion

This study was to evaluate the interproximal cleaning efficiency by the commercially available toothbrushes *in vitro*. After brushing test, experimental dental plaque was reduced; however every PRR was under 50%. Any type of bristle of the toothbrushes had difficulty in access around contact area of artificial-tooth (Fig. 2). The results of this study indicated that the use of commercially available manual toothbrushes alone was not directly applicable for interproximal cleaning. Interestingly, product A ($48.4 \pm 8.2\%$) showed greater reduction of interproximal plaque compared with product Z ($15.6 \pm 5.7\%$). This difference could be attributable to the properties in the toothbrushes. Several studies compared the ability of toothbrushes with various designs in removing interproximal plaque.[4,22–25] However, it was not yet to be understand which property, e.g. bristle stiffness, length of bristle, head area, bristle area, number of tufts, diameter of bristle, form of brush, step or total length, really had an effect on interproximal cleaning.

To our knowledge, the present study is the first to statistically analyze all properties extracted from commercially available manual toothbrushes for interproximal cleaning efficiency. In this study, the following models are used to explore the predictor: the mixed effect modeling, neural network model and response surface. The mixed effect modeling was used to construct a predictor for PRR. The neural network model was to calculate the predictive value of PRR. The response surface methodology was used to identify the levels of design factors or variables that optimize PRR. As a result of the mixed effect modeling, three key properties: bristle stiffness, number of tufts and total length had statistically significant effect on PRR. The normal type brush and small tufts could be more effective at interproximal access than the other types and tufts. And long handle might be easy to control the brushing pressure, although the grip depended on finger size of the operator. Subsequently, the neural network model confirmed the findings of the results that less tufts and longer handle were effective (Fig. 3). Response surface resulted total length more than 170.0 mm was required in order to obtain the high efficacy in case of soft and normal model type toothbrush and minimum tufts. When the number of tufts was increased, the total length was gradually longer and more than 180.0 mm was required. However, in case of hard type model, total handle more over 180.0 mm was required, even if number of tufts was minimum. When the number of tufts increased, the predictive value of PRR was constant regardless of the total length. Therefore, these results indicated that the balance of number of tufts and total length was important property to make the bristle reachable to the contact area of proximal area. However, it is difficult to get the well-balance among the 3 key properties. Therefore, in the present study, each stiffness model described unstable curve like three waves in Fig. 4. Nevertheless, these results should be considered to develop a novel toothbrush for interproximal cleaning.

The present study was performed with the experimental plaque model using the plaque-like substrate not but cariogenic bacteria or oral biofilm (Fig. 1). One of the advantages of this present design was that unstable biofilm adherence can be avoided on the interproximal surface. Many brushing tests have been proposed with different concepts.[4,8,9,23–32] A consensus about brushing test for plaque removal study has not been established. Further tests with different designs simulating to the oral environment should be carried out.

In conclusion, for the interproximal surface plaque removal tested in the present study, removal rate was not sufficient at all. In addition, PRR of the test toothbrushes was varied. The PRR was different depended on 3 key properties: stiffness, number of tufts and total length. Manufactures should be considered 3 major properties when they are to develop the new toothbrush.

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