

Robot and mechanical testing of a specialist manual toothbrush for cleaning efficacy and improved force control

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Abstract

Background: Toothbrushes require flexibility to access all dental surfaces and remove plaque effectively, but they should also aim to prevent or limit overbrushing and consequent damage to teeth and gums. In two studies, the physical properties and cleaning performance of specialist test toothbrushes with flexible necks were compared to a reference rigid-necked toothbrush.

Methods: In Study 1, a universal testing machine (Instron E 10000) with a specially designed setup was used to test the deflection behaviour of toothbrush head and neck. Untufted toothbrushes were fixed in a custom holder and force was applied to the head while the deflection was measured. In Study 2, one control and five test toothbrushes were assessed using a robot system to simulate the cleaning of artificial plaque from defined surfaces of artificial replicated human teeth in a model oral cavity (typodonts).

Results: Study 1 showed that the flexible-neck toothbrush deflected 2 to 2.5 times more than the rigid-neck reference toothbrush when same force was applied to the toothbrush head. Study 2 revealed that all five test toothbrushes showed statistically superior simulated plaque removal to the reference toothbrush. This superiority was observed for all test toothbrushes employing horizontal and rotating brushing action (all $p = 0.001$) but only three of the five toothbrushes when vertical brushing was employed (all $p = 0.001$). Cleaning efficacy of the test toothbrushes was demonstrated both interdentally and at the gumline locations. The Complete Protection toothbrush showed the most effective cleaning performance followed by the Repair and Protect and Rapid Relief toothbrushes.

Conclusion: The addition of a flexible-neck component to the toothbrush designs reduced stiffness and allowed more effective cleaning compared to rigid designs with controlled force distribution on the teeth and gums. This helped to provide plaque control at all risk areas in an *in vitro* robot model and could support good oral hygiene.

Trial registration: N/A

Background

The routine removal of plaque from exposed tooth surfaces using manual toothbrushes remains a critical component of oral health. This is emphasised by infrequent brushing being associated with increased incidence of dental caries and periodontal disease.¹⁻³ Toothbrushes should provide flexibility, allowing the brush fibres to reach all the accessible dental surfaces. Toothbrushes must also allow enough force to be applied for effective plaque removal but importantly, they should also prevent overbrushing.⁴⁻⁷ Such use of improper or excessive force during toothbrushing is a known risk factor for developing cervical abrasion lesions, as well as gingival recession, which in turn can cause dentine hypersensitivity.^{8,9}

Clinical studies are commonly used to evaluate how new toothbrushes perform in the hands of test subjects, however, variations in patients' oral health, brushing technique, applied force, and compliance with instructions, along with other inconsistencies, can result in data that are not entirely comparable and

consequentially limit their reliability.^{10,11} However, robot-based brushing models can play a key role in assessing toothbrush performance due to their ability to reproducibly apply the consistent force and cleaning action to a set of typodonts coated with uniform quantities of 'artificial' plaque for each test run.^{12,13}

During the past 25 years, increasingly sophisticated versions of these robot systems have been developed to more accurately compare the performance of toothbrushes, and have provided valuable information allowing objective comparisons between designs.¹⁴⁻¹⁶ These systems have been used to assess plaque removal and determine the effects of brush wear and dentifrice use.

This article reports data from two studies that assessed experimental toothbrush designs (GSK Consumer Health), which incorporates a flexible element in their necks, designed to look like a ball joint, between the toothbrush head and handle. These product designs aim to change the angle of the brushing head towards the inbetween regions of buccal and lingual/palatinal tooth surfaces, and to reduce the brushing force that is transmitted to the tooth and gum surfaces. This feature improves the biophysical brushing action and mitigates the risks for tooth wear, receding gums, and dentine hypersensitivity while also delivering efficacious cleaning. These flexible-neck toothbrush designs were compared to a classic rigid-neck design, hereafter referred to as the 'control' toothbrush. To evaluate the contact force and deflection behaviour of the flexible- and rigid-neck toothbrushes, they were mechanically tested without bristles in the first study. To assess the cleaning performance of this flexible-neck design, five variants, differentiated by their distinct bristle configurations (hereafter collectively referred to as 'test' toothbrushes) were assessed using a robot tooth-cleaning evaluation system in the second study. These test toothbrushes were assessed in comparison to a control toothbrush with a 'standard' flat-trim bristle configuration.

The purpose of these current studies was, firstly, to mechanically evaluate the test and control toothbrushes to compare the levels of deflection as a function of the force applied. The second of the two studies specifically aimed to compare the cleaning efficacy of five test versus control toothbrushes using a robot test of cleaning efficacy by plaque planimetry and at gentle brushing forces (2.5 newtons [N]).

Methods

Study 1 – Mechanical testing of toothbrush deflection

This study compared test toothbrushes (flexible neck, ten samples without bristles) with the control toothbrush (rigid neck, ten samples without bristles, Jubilee Toothbrush). A universal testing device (ElectroPuls™ E10000 Linear-Torsion All-Electric Dynamic Test Instrument by Instron, GmbH, Germany) was used to measure the resistance force of the toothbrush heads while deflecting them with a roller force applicator equipped with a load cell (Dynacell 250 N by Instron, GmbH, Germany) (**Figure 1**). The toothbrush handles were fixed in position using a 3D-printed form-fitted holder and epoxy resin to prevent uncontrolled bending of the toothbrush. The form-fitting holder was necessary because a conventional fixation for the toothbrushes creates additional pivot points. This would result in bending of the handle while testing, which does not reflect how toothbrushes behave in practical use, and affects the resulting

forces. Using individual sample holders increases the contact surface on the handle and reduces the amount of pivot points. This provides a good representation of actual toothbrushing and minimises the influence of the handle on the measurements.

To record force-deflection diagrams, ten samples per toothbrush type were tested. Force was applied to the handle until a maximum head deflection of 10 mm was reached. In the deflection test, the starting position of the roller force applicator was 1–2 mm above the toothbrush head and 60 mm away from the thumb position of the handle. For testing, the roller force applicator moved downwards (10 mm) and deflected the toothbrush head. The resulting resistance force was measured by a load cell (**Figures 1, 2a and 2b**).

Study 2 – Cleaning efficacy by plaque planimetry

The pre-test was conducted to compare brushing at forces of 2.5 N and 3.5 N. This showed no significant differences in toothbrush performance between those two forces. It was therefore decided to test all six toothbrushes with the lower force of 2.5 N only. This study used a clinically validated robot test of six toothbrushes on typodonts in anatomic position (KaVo®) assessing efficacy with automated plaque planimetry (APP) assessments at 30 fields per tooth (**Supplementary Figure 1**). The five test versus one control toothbrushes assessed in this study can be seen in **Figure 3**. The test toothbrushes were: Complete Protection Soft (ComPro), True White Medium (TrueWhi), Sensitivity & Gum Soft (SensGu), Repair and Protect Soft (RepPro) and Rapid Relief Soft (RapRe). The control or reference toothbrush was the Jubilee Toothbrush (RefJub).

Three different brushing movements were assessed in Study 2: horizontal, vertical and rotating. The brushing force was 2.5 N and seven distinct runs were conducted per movement. The teeth were tested at sites buccally and lingually, mesially and distally with full statistical support tests.

The evaluation process compared five test toothbrushes with the control toothbrush. This involved differentiation of gumline and interproximal regions (ABCDF-fields) of buccal and lingual sites (the locations of these APP tooth fields are given in the **Supplementary Material**). Evaluation also included cleaning efficacy tooth-by-tooth of all interproximal, buccal and lingual sites; root fields W buccally and W lingually, W1W2 mesially and W1W2 distally; total cleaning efficacy of all buccal and lingual, mesial and distal, coronal and root sites (30 fields per tooth), and illustration of brushing efficacy at these sites with box plots, error bars and tables (see **Supplementary Figure 2** for locations of these tooth fields). In the statistical analysis, the Kolmogorov–Smirnov test was applied to test the cleaning efficacy of the toothbrushes by tooth surface variables. However, the null hypothesis of normality was rejected as performance of the toothbrushes was not normally distributed with equivalent variances, therefore analysis was performed using the non-parametric Wilcoxon–Mann–Whitney (WMW) test. All toothbrushes were tested against each other. The WMW test can be applied to ordinal or unknown disturbances, contrary to the t-test, and it is nearly as efficient as the parametric t-test (power efficiency of the WMW test: 95%>power efficiency>90%).

For all two-tailed tests of differences in cleaning efficacy between the six toothbrushes, the significance level was set at the basic p-value of $\alpha = 0.05$ (5%). Statistical analyses were performed using IBM SPSS® professional statistics software, release 26, 64-bit version.

Results

Study 1 – Mechanical testing of toothbrush deflection

During mechanical testing, the test toothbrushes and the control toothbrushes behaved differently. For the test toothbrushes with flexible necks, at the starting position, the head of the toothbrush was straight, although following the start of deflection, the brush head flexed at both pivot points (thumb position and flexible neck, see **Figure 2a/2b**). This flexing was slightly larger at the flexible neck. At maximum deflection, the brush head was significantly bent. The bending occurred mainly through deformation at the flexible neck. For the control toothbrush, at the starting position, the head of the toothbrush was unchanged with a small angle at the end of the head. After the deflection started, the toothbrush head was bent at both pivot points (thumb position and start of head). The bending was slightly larger at the toothbrush head. At maximum deflection, the toothbrush head was significantly bent due to deformation of the smallest cross section at the end of the toothbrush head. When force was further exerted on a test toothbrush, the bending occurred mainly at the flex zone, whereas the entire neck and head were deflected for the control toothbrush. At an applied force of 2.5 N, a mean deflection of 3.9 ± 0.1 mm was measured for the test toothbrush, and 1.6 ± 0.1 mm for the control toothbrush (**Figure 4**). The entire force-deflection progression showed that the test toothbrush is deflected 2–2.5 times more than the control toothbrush when the same bending force was applied (**Figure 4**).

Study 2 – Cleaning efficacy by plaque planimetry

After a pre-test assessment of two different brushing forces (2.5 N vs 3.5 N) it was decided to test all the toothbrushes at the lower brushing force of 2.5 N only, which a bending assessment indicated was associated with 75% bending of the test toothbrushes. All of the five test toothbrushes were statistically superior in performance in terms of artificial plaque removal (%) compared to the control toothbrush ($p < 0.001$ for most comparisons). The superior performance of the test toothbrushes was maintained at all crown risk areas, including ABCDF next to the gumline, mesial and distal inbetween fields. This is shown in the WMW U statistics and associated probabilities for total cleaning effects of the five test toothbrushes versus the control toothbrush in **Table 1** and in **Supplementary Tables 4–6**.

A comparison of interdental and gumline cleaning for the test toothbrushes versus the control toothbrush is given in **Figure 5**. The plots show means and standard deviations (as error bars) for plaque removal by the six toothbrushes using horizontal, rotating and vertical brushing movements. In each case, the superiority in performance by the flexible-neck designs compared to the control toothbrush was shown. This difference was most apparent for mesial, distal and ABCDF buccal locations for all three types of brushing action.

For horizontal, rotating and vertical cleaning efficacy parameters, the ComPro toothbrush showed the best overall plaque removal performance. The next best-performing test toothbrushes were the RepPro and the RapRe. These three toothbrushes tended to perform better when compared to the other test toothbrush counterparts (TrueWhi and SensGu) but the differences between them were quite small (**Figure 5, Table 1, and Supplementary Figure 3**). However, all of the test toothbrushes performed significantly better than the rigid control toothbrush, which was the poorest-performing toothbrush (**Figure 5, Table 1, and Supplementary Figure 3**).

The average cleaning score across three movements for the ComPro test toothbrush was 64.12% compared to the control toothbrush, which was 43.11%. The brushing efficacy was generally greater for the five test toothbrushes in terms of access to interdental spaces, exposed root surfaces and differing tooth types, compared to the control toothbrush. Horizontal and rotating brush movements with the test toothbrushes were significantly more effective in removing simulated plaque than for the control toothbrush. Vertical brushing movements were also more effective with the test toothbrushes, although only for 3 out of 5 test toothbrushes.

An analysis of single replicated human teeth showed that there was optimum plaque control at incisors (up to 99.75%) after horizontal brushing in interdental risk areas, followed by wisdom teeth (up to 64.06%) then canines, premolars and molars (up to 45.72%) (See **Supplementary Tables 1–6**).

Discussion

The mechanical testing in the two reported studies shows that the addition of a flexible neck to the toothbrush designs significantly reduces stiffness in the neck and head regions compared to rigid-neck toothbrushes. This can help reduce the force applied to the oral mucosa and tooth surfaces. Moreover, this flexibility is apparent at force levels typically used in manual toothbrushing. The tests of toothbrush deflection clearly showed very different force-deflection curves, with the test toothbrush showing 2.5 times lower measured force at the head than the control toothbrush. This deflection arose as a result of the flexible neck component rather than different leverage effects or the angle of the brush heads. The presence of the flexible neck results in smaller moment arm for the test toothbrushes, resulting in lower bending moments on the tooth surface compared to the control toothbrushes. The lower force and moment produced by the test toothbrushes can help provide a more gentle brushing action and significantly reduces the risk of overbrushing and gum damage.

The force-deflection curve indicates that when used for cleaning, the test toothbrushes would have a more controlled force distribution of brushes on the teeth. The curve also indicates that high forces are achieved with small deformations. The force steps are smaller with the test compared to the control toothbrush, enabling improved force control and better cleaning.

The comparison of the five flexible-neck test designs with the control design consistently demonstrated improved performance in terms of cleaning efficacy over multiple different tooth surfaces when the brushing movement was either horizontal or rotating. With vertical brushing movement, however, the clear

superiority of performance was less marked. This is due to the fact that how the flexible neck bends supports horizontal/rotating motion, but vertical motion limits the force transfer, and the neck handle reacts in a similar manner to a rigid toothbrush. It should be noted that the most common brushing actions are horizontal and rotating^{13,17,18} and their efficacy is clearly supported by the current findings, even though the efficacy achieved by vertical brushing movements was at least comparable to that achieved by rigid brushing handles.

The flexible toothbrush neck contributes to effective plaque control in hidden biofilm-accumulating regions inbetween the teeth and around exposed roots. The majority of consumers worldwide, when using toothbrushes, exhibit random brushing habits with horizontal scrubbing, rotating and gliding actions; toothbrushes with high neck flexibility are more suited to this usage than more rigid designs (**Supplementary Videos 1–3**). This advantage of toothbrushes with greater neck flexibility may be supported by future clinical trial data.

The analysis of single teeth also showed superior cleaning performance at multiple different sites by the flexible-neck designs. This cleaning was most effective for incisors, followed by wisdom teeth, canines, premolars and molars. This could be an issue of access to individual teeth and may be worth further investigation. The cleaning efficacy study advances previous work on robot typodonts, real toothbrushing, and visualisation and quantification of simulated plaque removal.¹³⁻¹⁶ This technology is important for the accurate assessment of tooth cleaning and in the development of new approaches in oral hygiene.

Conclusions

These studies confirm that the novel toothbrush designs, with the addition of a flexible component in the neck of the test toothbrushes, increase neck flexibility under typical toothbrushing forces. This design reduces the force transmitted from the toothbrush to dental surfaces, resulting in lower shear and compressive stresses, and consequently less damage to the teeth and gums.

The cleaning efficacy of the test toothbrushes, as tested by using a clinically validated, *in vitro* robot model employing three different brushing movements and standardised brushing forces (2.5 N), indicates that the five test flexible-neck designs provide optimal plaque control at all risk areas and their single planimetric fields. This contributes to the prevention of dental caries and gingivitis, and potentially improves dental health.

In future planned studies, torsional movements around the long axis of the toothbrush handle, and their effects, could also be measured. In addition, the inner stress distribution of the entire toothbrush body could be determined to better understand mechanical behaviour during force exertion. This work could provide further insights, leading to improvements in toothbrush design and performance for better oral health.

Abbreviations

3D: three dimensional; APP: automated plaque planimetry; ComPro: Complete Protection Soft; N: newton; RapRe: Rapid Relief Soft; RefJub: Jubilee Toothbrush; RepPro: Repair & Protect Soft; SensGu: Sensitivity & Gum Soft; TrueWhi: True White Medium; WMW: Wilcoxon–Mann–Whitney

Declarations

Ethics approval and consent to participate

Both study arms were executed *in vitro* and the teeth used in the robot toothbrushing model were replicated from human teeth in KaVo plastics. The simulated plaque exhibiting physiological characteristics was clinically validated.

Consent for publication

Not applicable

Availability of data and materials

The complete datasets generated and/or analysed during the current study are not publicly available in the manuscript due to their lack of relevance to this article and word count considerations. Although, they are available from the corresponding author on reasonable request.

Competing interests

AA is an employee of GSK Consumer Health.

AK, MG, AR and SS are employees of the Fraunhofer Institute for Microstructure of Materials and Systems, which has received research funding from GSK Consumer Health.

PG and TL are employees of the Institute for Oral Medicine at the Witten/Herdecke University, which has received research funding from GSK Consumer Health.

Funding

Funding for this study was provided by GSK Consumer Health.

Authors' contributions

AA played an active role in the study design and interpretation of Studies 1 and 2. AK, MG, AR and SS all participated in the study design, data collection, analysis and interpretation of Study 1. PG and TL participated in the study design, data collection, analysis and interpretation of Study 2. All authors have read and approved the manuscript.

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Tables

Table 1. Cleaning efficacy using A. horizontal, B. rotating and C. vertical toothbrush movements

A. horizontal brushing movement					
Toothbrush type Mean total % plaque removal ± SD	ComPro 69.4 ± 2.5	TrueWhi 63.7 ± 4.1	SensGu 65.9 ± 2.1	RepPro 64.6 ± 3.0	RapRe 65.0 ± 1.8
ComPro 69.4 ± 2.5	N/A	-	-	-	-
TrueWhi 63.7 ± 4.1	4.0 <i>p</i> = 0.007*	N/A	-	-	-
SensGu 65.9 ± 2.1	5.0 <i>p</i> = 0.011*	NS	N/A	-	-
RepPro 64.6 ± 3.0	4.0 <i>p</i> = 0.007*	6.0 <i>p</i> = 0.035*	3.0 <i>p</i> = 0.004*	N/A	-
RapRe 65.0 ± 1.8	3.0 <i>p</i> = 0.004*	NS	NS	NS	N/A
Control 47.5 ± 2.4	0.0 <i>p</i> = 0.001	0.0 <i>p</i> = 0.001	0.0 <i>p</i> = 0.001	0.0 <i>p</i> = 0.001	0.0 <i>p</i> = 0.001

B. Rotating brushing movement					
Toothbrush type Mean total % plaque removal ± SD	ComPro	TrueWhi	SensGu	RepPro	RapRe
	69.8 ± 3.6	64.6 ± 1.6	66.0 ± 2.7	63.3 ± 5.2	65.6 ± 2.6
ComPro 69.8 ± 3.6	N/A	-	-	-	-
TrueWhi 64.6 ± 1.6	5.0 <i>p</i> = 0.011*	N/A	-	-	-
SensGu 66.0 ± 2.7	8.0 <i>p</i> = 0.038*	NS	N/A	-	-
RepPro 63.3 ± 5.2	8.0 <i>p</i> = 0.038*	NS	NS	N/A	-
RapRe 65.6 ± 2.6	8.0 <i>p</i> = 0.038*	NS	NS	NS	N/A
Control 46.0 ± 2.2	0.0 <i>p</i> = 0.001	0.0 <i>p</i> = 0.001	0.0 <i>p</i> = 0.001	0.0 <i>p</i> = 0.001	0.0 <i>p</i> = 0.001

C. Vertical brushing movement					
Toothbrush type Mean total % plaque removal ± SD	ComPro	TrueWhi	SensGu	RepPro	RapRe
	53.2 ± 6.1	36.5 ± 5.0	40.2 ± 5.7	51.5 ± 5.3	51.1 ± 2.1
ComPro 53.2 ± 6.1	N/A	-	-	-	-
TrueWhi 36.5 ± 5.0	2.0 <i>p</i> = 0.002	N/A	-	-	-
SensGu 40.2 ± 5.7	4.0 <i>p</i> = 0.007*	NS	N/A	-	-
RepPro 51.5 ± 5.3	NS	1.0 <i>p</i> = 0.001	4.0 <i>p</i> = 0.007*	N/A	-
RapRe 51.1 ± 2.1	NS	0.0 <i>p</i> = 0.001	0.0 <i>p</i> = 0.001	24.0 <i>p</i> = 1.000	N/A
Control 35.9 ± 2.0	0.0 <i>p</i> = 0.001	NS	NS	0.0 <i>p</i> = 0.001	0.0 <i>p</i> = 0.001

Data are Wilcoxon–Mann–Whitney (WMW) U-statistic and *p*-values. The cleaning efficacy (% plaque removal) of six toothbrushes (ComPro, TrueWhi, SensGu, RepPro, RapRe, Control) was assessed using APP-index at 30 fields per tooth using three different brushing movements. The total values given are derived from % plaque removal using brushing of the following areas: buccal, mesial, distal, ABCDF buccal, ABCDF lingual, W buccal, W lingual, W1+W2 mesial, W1+W2 distal. The cleaning efficacy (% plaque

removal) of each single toothbrush was compared against each other via a WMW test (*not significant using Bonferroni correction). APP: automated plaque planimetry; ComPro: Complete Protection Soft; N/A: not applicable; NS: not significant (on either test); RapRe: Rapid Relief Soft; RepPro: Repair & Protect Soft; SD, standard deviation; SensGu: Sensitivity & Gum Soft; TrueWhi: True White Medium; WMW: Wilcoxon–Mann–Whitney.

Figures



Figure 1

Schematic for mechanical testing of toothbrush samples

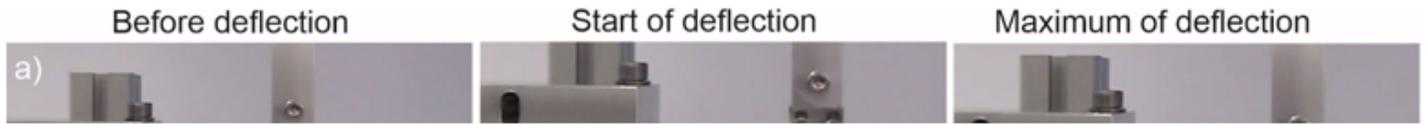
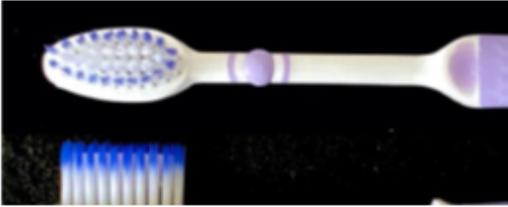


Figure 2

Mechanical testing of the test (a) and control toothbrush (b)

Complete Protection Soft (ComPro)



True White Medium (TrueWhi)



Figure 3

Test and control toothbrushes

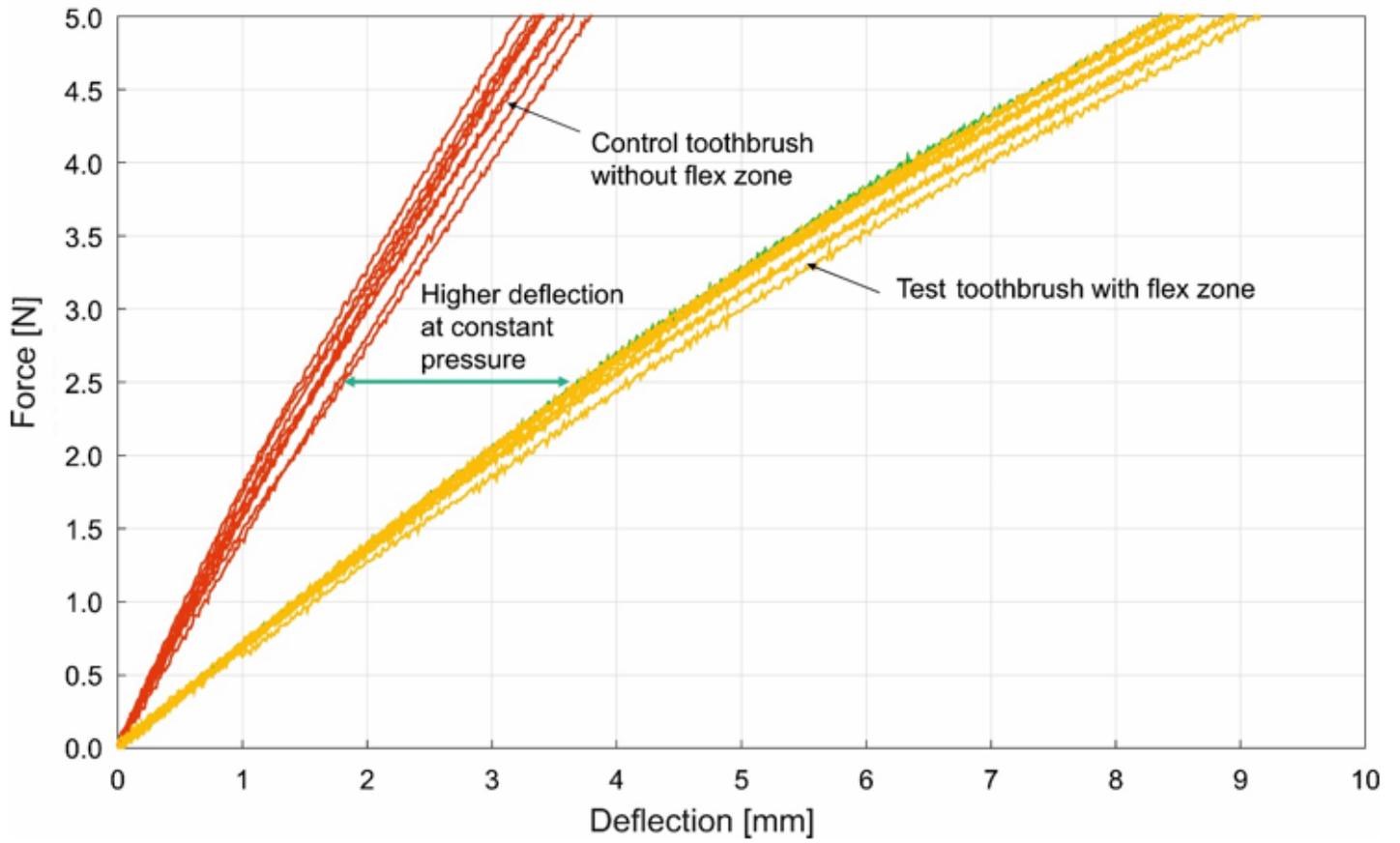


Figure 4

Force-deflection curves for test vs control toothbrushes At the same force, the test toothbrush is deflected 2–2.5 times more than the control toothbrush.

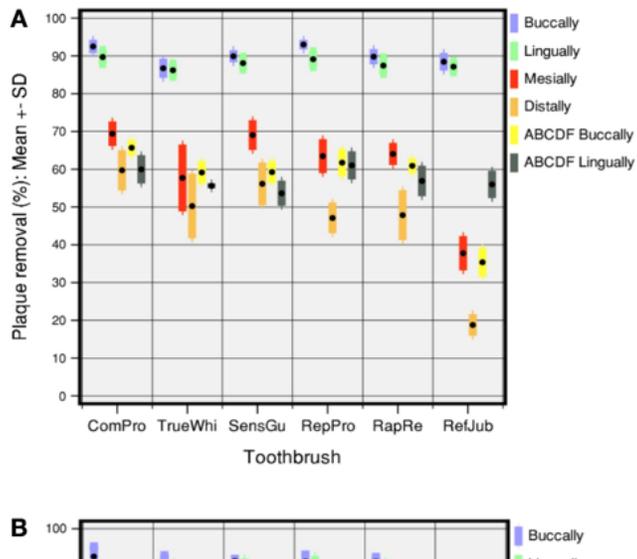


Figure 5

Cleaning efficacy across planimetric coronal fields using A. horizontal, B. rotating and C. vertical brushing Plaque removal percentage at the four sites per each tooth (smooth surfaces buccally and lingually, in between teeth mesially and distally, ABCDF risk area next to the gumline). Black dots represent mean values, coloured error bars represent \pm 1 standard deviation.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryAppendixForRESubmission.docx](#)
- [SVVerticalbrushingmovement2.5NCompleteProtectionSoft7.mp4](#)
- [SV2Horizontalbrushingmovement2.5NCompleteProtectionSoft1.mp4](#)
- [SV3Rotatingbrushingmovement2.5NCompleteProtectionSoft1.mp4](#)