A new occlusal surface design for artificial posterior teeth to achieve high masticatory performance

Yuki Hashimoto DDS[1], Kyoko Sugimoto DDS, PhD[2,*], Yuki Tanaka DDS[1], Kazuhiro Oki DDS, PhD[1], Shogo Minagi DDS, PhD[1]

1 Department of Occlusal and Oral Functional Rehabilitation, Okayama University, Okayama, Japan
2 Center for the Development of Medical and Health Care Education, Okayama University, Okayama, Japan

* Corresponding author: Kyoko Sugimoto
Center for the Development of Medical and Health Care Education, Okayama University, 2-5-1 Shikata-cho, Kita-ku, Okayama 700-8525, Japan
Tel: +81 8 6235 6687
fax: +81 8 6235 6689
E-mail address: k-sugi@md.okayama-u.ac.jp

Abstract

Purpose: The low masticatory efficiency of denture prostheses impairs the ability of wearers to consume high-fiber foods. Hence, artificial teeth with high masticatory efficiency are required. This study aimed to establish an occlusal surface design for posterior artificial teeth in denture prostheses that is compatible with the existing artificial teeth arrangement and that has high masticatory efficiency for the comminution of raw vegetables.

Methods: A masticatory simulator for occluding complete dentures was used to evaluate the masticatory efficiency of four occlusal surface designs, i.e., with parallel grooves occluding at right angles to the opposing teeth, groove depths of 1 and 0.5 mm, and inter-groove distances of 1, 2, and 3 mm. Raw carrots, rice, raw lettuce, chicken breasts, and peanuts were used as test foods to evaluate food comminution.

Results: Grooved occlusal surface designs with a 1-mm groove depth and a 2- or 3-mm inter-groove distance demonstrated significantly greater masticatory efficiency than the conventional occlusal form ($p < 0.05$).

Conclusions: The superiority of grooved designs over the conventional design was particularly evident for lettuce and raw carrots in this study, both of which are considered difficult foods to chew with complete dentures.

1. Introduction

As the population ages worldwide, there are increasing reports of functional limitations in speaking and eating that result from tooth loss and that affect quality of life [1]. Masticatory function in edentulous patients is often affected by the condition of the alveolar ridge. The number of masticatory cycles required to chew a standard piece of food progressively increases with age, with less comminution achieved in a longer chewing sequence [2]. Studies using food questionnaires reveal that tooth loss leads to dietary modifications as people choose foods that are easier to chew [3]. Furthermore, elderly edentulous people avoid many types of food, particularly raw vegetables, which they cannot effectively chew with conventional complete dentures [3].

Although the number of patients undergoing oral rehabilitation with the use of osseo-integrated implants has increased [4], conventional complete dentures remain the most common treatment for edentulous patients [5]. The occlusal surface design of artificial teeth plays an important role in the masticatory efficiency of complete dentures. Hence, many kinds of occlusal surface and the functional differences among them have been reported to date [6, 7]. Bladed teeth are one of the most common and effective non-anatomical designs [6, 8]. However, bladed teeth are not available for all edentulous patients worldwide because of lack of commercial availability and expense. Therefore, occlusal surface designs that can easily be manufactured and that markedly improve mastication would greatly benefit edentulous patients and could influence the properties of future denture prosthodontics.

As Levin describes [8], occlusal facets cut fibrous food, which is then pulverized. The efficiency of mastication depends on the exact interactions between numerous small, sharp-edged facets on opposing teeth. When designing occlusal surfaces, the most important aspect is their potential compatibility with any existing artificial tooth arrangements, i.e., full-balanced occlusion, lingualized occlusion [9], or even the heavily worn occlusal surfaces of old dentures. We recently reported [10] a new design for a molar occlusal surface, which is a simple grooved design, to fulfill the above necessity for denture prostheses in elderly patients.

The purpose of this study was to evaluate the properties of different occlusal surface groove designs to determine the best design for improving masticatory efficiency.

2. Materials and methods

2.1. Occlusal surface design

Experimental upper and lower complete dentures were designed to mount on a masticatory simulator. The artificial teeth (A5A-500; Nissin Dental Products, Inc., Kyoto, Japan) were screw-retained to experimental complete dentures and were exchangeable to allow direct comparisons between artificial tooth designs. The artificial teeth were made of melamine resin with a Vickers hardness of 44.0 HV, and a Knoop hardness of 50 GPa. The experimental dentures were first mounted onto a stone cast on a semi-adjustable articulator, where the maxillomandibular relationship and slot adjustment were made equivalent to those of the masticatory simulator. Selective grinding of the artificial teeth was performed on the articulator to achieve lingualized occlusion. The articulator was adjusted as follows: horizontal condylar path angle, 15°; sagittal condylar path angle, 30°; incisal guide, 0°. After selective grinding and milling-in using carborundum-glycerin paste, parallel grooves were prepared at a 45° angle to the dental arch, as shown in Figure 1, for each subsequently described groove design group. The direction of grooves on the maxillary molars was designed to be orthogonally oriented to those on the mandibular molars when occluded (Fig. 1a). Figure 1b shows an example of a clinical case of dentures with grooved teeth.

Five occlusal surface designs were used to evaluate masticatory performance. After the selective grinding and milling-in described above, grooves were prepared on the occlusal surfaces with a diamond disc (H362F080; Mokuda Dental Co., Ltd., Kobe, Japan) and a milling machine (FF230; Kiso Power Tool. Mfg. Co. Ltd., Osaka, Japan). The width of each groove was 1 mm. Three different inter-groove distance conditions, namely 1 mm (G1), 2 mm (G2), and 3 mm (G3), were used. The depth of the grooves for G1, G2, and G3 was 1 mm at the buccolingual center of each artificial molar tooth, and 0 mm at the buccal and lingual edges of the occlusal surface. To evaluate the effects of groove depth, the G2(0.5) condition was also used, in which the groove depth was 0.5 mm at the buccolingual center of each artificial molar tooth, and 0 mm at the buccal and lingual edges of the occlusal surface. As a control, artificial molar teeth were used after selective grinding with no groove prepared (G−).

2.2. Masticatory simulator

The masticatory performance of complete dentures with each artificial tooth design was evaluated using a masticatory simulator. As shown in Figure 2a, a semi-adjustable articulator (Hanau 158-3; Teledyne Hanau, Buffalo, NY, USA) was installed on a power bench (DDL-5556N; Juki Corporation, Tokyo, Japan). The horizontal condylar path angle of the articulator was set at 15° and the sagittal condylar path angle was set at 30°. Masticatory force was generated by a weight fixed on the upper member that exerted 52.9 N (5.4 kgf) on the mandibular first molar, according to the reported mean occlusal force for complete denture wearers [11]. The horizontal mandibular position was returned to the intercuspal position with two sets of dampers and springs installed symmetrically on the upper member. The edentulous maxillary and mandibular casts were made of polymethyl methacrylate resin and covered with a silicone layer 1.5-mm thick to simulate the mechanical properties of mucosal tissue. All experiments were conducted using the same set of maxillary and mandibular complete denture bases fabricated to fit the surface of the silicone-covered cast by changing the screw-retained artificial teeth. Masticatory cycles were performed at 1 cycle/s, according to the report by Okada *et al*. [12], by pulling the pull-up ring installed on the extended rod of the upper member (Fig. 2a) using the traction of the power bench. The closing phase of the masticatory mandibular movement was guided laterally by the guiding rod gliding on the guiding plate. A mean trace of three masticatory cycles for the incisal point on the coronal plane is shown in Figure 2b. The mean maximal jaw opening during the masticatory cycle was 18 mm at the incisal point and the mean maximal lateral deviation of the incisal point during the masticatory cycle was 3.9 mm. To catch masticated food particles falling from the occlusal surface, a rubber dam was installed around the premolars and molars. In order to avoid the possible masticatory error because of the scattering of the masticated particles, the particles on the rubber dam were retrieved manually and placed on the center of the occlusal surface of the first molar every two masticatory cycles.

The test foods used to evaluate masticatory performance were raw carrots (10 × 10 × 5 mm), boiled chicken breasts (10 × 10 × 5 mm), lettuce (20 × 10 × 1 mm), 10 grains of cooked rice (Freeze-Dried Jasmine Rice; Allied Corporation, Yokohama, Japan), and half a peanut. The chicken breast was boiled for 5 min just before the experiment. The freeze-dried cooked rice was rehydrated just before the experiment in accordance with the manufacturer's instructions [13, 14]. Each test food was placed on the right first molar and masticated in the masticatory simulator for 3, 6, 9, 12, 15, 18, and 21 cycles to clarify the effect of artificial teeth in the early stages of mastication [14]. All masticatory trials were performed in triplicate. For each trial, 1 mL of artificial saliva (Salivert; Teijin, Osaka, Japan) containing 0.29 mg/mL mucin [15, 16] was added to the test food just before the masticatory trial. Food particles trapped on the rubber dam were manually returned to the occlusal surface of the lower first molar every two masticatory cycles with a small brush.

2.3. Food bolus processing

Food bolus processing was performed according to the method of Sugimoto *et al*. [14]. Food bolus samples were collected in a 0.8-cm^3 vessel. One 0.8-cm^3 sample was taken from each test food bolus for digital imaging. The samples were washed with 25 mL 0.032% fatty acid alkanolamide solution. Next, they were washed with distilled water in a stainless steel sieve with a 0.2-mm mesh. The processed particles were then retrieved and dispersed in 0.06% benzalkonium chloride in plastic Petri dishes.

2.4. Food particle analysis

Dark-field images of the bolus samples were obtained with a masticatory efficiency evaluation system (SME-002; Shofu, Inc., Kyoto, Japan) equipped with a digital camera and a double dark-field illumination system. Digital images were binarized using one identical set of optical threshold conditions of hue, saturation, and lightness, yielding the virtual diameter and area of each particle in the food sample [17].

The food particle size index (SI) and homogeneity index (HI) were calculated from the virtual diameter and area of particles with a diameter > 2 mm, according to the method of Sugimoto *et al*. [17]. HI represents the slope of the regression line of the logarithmic particle area array and SI represents the intercept of the regression line. Therefore, HI values closer to 0 indicate higher homogeneity of observed particle size, and smaller SI values indicate that food was masticated into smaller particles. The median HI and its corresponding SI were used as representative values for each masticatory condition. Regardless of the food material, an HI value smaller than 0.1 and an SI value smaller than 1.62 is a reported requirement for normal mastication ability in healthy young adults [14].

2.5. Statistics

Levene's test was used to examine the homogeneity of the variances of HI and SI. When homogeneity of the variances was rejected, multiple comparisons were performed using the Friedman test to evaluate the differences in HI and SI among the artificial tooth designs for each test food. Data analyses were performed with SPSS software (IBM SPSS Statistics version 20.0; IBM Corp., Armonk, NY, USA). A significance level of $p < 0.05$ was used in this study.

3. Results

Typical digital images of lettuce after 3, 9, 15, and 21 mastication cycles with the five artificial tooth designs are shown in Figure 3. Marked differences in the comminution of the lettuce were evident, with particularly finely comminuted particles produced by G2 and G3 compared with G(−). Figure 4 shows the HI and SI values for each test food and occlusal surface design tested. The dotted lines in Figure 4 show the HI threshold of 0.1 and SI threshold of 1.62, indicating the limit of the normal mastication range for young adults [14]. For peanuts and rice, fewer masticatory cycles were necessary to produce SI and HI values in the normal range, regardless of occlusal surface design. For chicken breasts, the comminution effects varied depending on the design of the artificial teeth. G2 and G3 resulted in HI and SI values in the normal range after nine mastication cycles. The values for G(−) reached the normal range after 21 mastication cycles. Although G2 and G3 reached the normal HI and SI range in 12 masticatory cycles for raw carrots, G(−) did not reach the normal range even after 21 cycles. The progress of mastication was markedly slower for lettuce than for the other test foods. After 21 masticatory cycles, only G3 was able to reach the normal HI and SI range with lettuce. The HI and SI values showed that G1 was the most effective design for the initial comminution of lettuce. However, the comminution effect of G1 did not reach the normal range even after 21 cycles. The comminution effects of G(−) on lettuce remained unchanged between 12 and 21 cycles of mastication.

Because Levene's test rejected homogeneity of the variances, multiple comparisons were performed using the Friedman test. The results of the multiple comparisons analysis of the artificial tooth designs for each test food are summarized in Table 1. Mastication of chicken breasts showed characteristic properties, particularly for fewer masticatory strokes. For 6, 9, and 15 masticatory cycles with chicken, significant differences in HI were evident between G(−) and G1, G2, and G2(0.5). For raw lettuce, which is one of the test foods that is difficult for complete denture wearers to chew, the grooved designs caused rapid decreases in HI and SI toward the normal range with fewer masticatory cycles. Although only G3 showed a significant difference ($p < 0.05$) in HI at 21 masticatory cycles compared with G(−),the grooved designs showed a marked trend toward lettuce comminution compared with G(−). For raw carrots, G2 and G3 showed particularly high masticatory efficiency and required fewer masticatory cycles to reach the normal comminution range. For rice, initial increases in HI were observed after six cycles for G(−), G2, G3, and G2(0.5), followed by fair progression of comminution into the normal range. Regarding peanuts, only one condition, G(−) versus G1 at 18 masticatory cycles, showed a statistical difference. All of the artificial teeth achieved good mastication of peanuts, regardless of occlusal surface design, with similar progression of comminution.

4. Discussion

4.1. Test food materials

The effects of the occlusal surface design varied depending on the food material tested. For raw carrots and chicken breasts, different designs produced markedly different effects, particularly when the number of masticatory cycles was small. G(−) had low masticatory efficiency for raw carrots and chicken breasts, whereas G2 and G3 reached the normal range with fewer masticatory cycles. G1 seemed to be most affected by differences in food materials, demonstrating an excellent ability to masticate chicken breasts, but reduced efficiency in masticating raw carrots, particularly when the number of masticatory cycles was small. Because we evaluated masticatory performance under a single prescribed occlusal force (52.9 N on the mandibular first molar), we collected no data on the minimal pressure exerted on the denture-supporting tissue during comminution of the food materials. However, assuming that edentulous patients exert occlusal force until food comminution is achieved, fewer masticatory cycles would imply lower exertion and less masticatory force exerted on the alveolar ridge.

Differences in masticatory performance after large numbers of masticatory cycles can indicate whether or not edentulous patients would be able to consume the food materials under examination. For raw lettuce, which is a typical leafy vegetable, the progress of comminution was different from that of the other food materials. G(−) achieved less comminution than the other designs, even after 21 masticatory cycles. These findings are consistent with the tendency of elderly people to experience difficulty eating leafy vegetables, particularly in their raw state [18-20]. Visual observation of food bolus samples collected after mastication with G(−) revealed that most parts of the raw lettuce were merely pressed and flattened, rather than shredded into pieces, even after 21 mastication cycles. Conversely, with G2 and G3, the raw lettuce was shredded after approximately nine masticatory cycles. It should be noted that nine masticatory cycles is within the typical range of masticatory cycles and that effective shredding would occur within that range in elderly people. These findings strongly suggest that this grooved design is effective for mastication and may facilitate the consumption of fibrous vegetables in elderly edentulous patients.

For rice and peanuts, no marked differences were evident among the occlusal surface designs. Comminution was observed after few masticatory cycles. Rice is a food material that naturally consists of evenly sized particles. Therefore, the initial increase in HI observed for G(−), G2, G3, and G2(0.5) after six masticatory cycles reflects decreased homogeneity resulting from splitting of the rice particles during comminution. Because peanuts are crushable, they were well comminuted with fewer masticatory cycles when the masticatory force was higher than that necessary for crushing. Because edentulous patients can easily exert an occlusal force of 50 N with denture prostheses, occlusal surface design may have a smaller effect on the mastication of and propensity to consume crushable foods like peanuts. However, the effect of occlusal surface design on the consumption of crushable foods may be more significant in patients with a lower maximum occlusal force. Future studies are needed to measure the pressures exerted on the mucosal surface of the experimental denture base. Although edentulous patients tend to avoid eating nuts, this could be to avoid pain caused by small particles getting trapped under the denture base, which is a separate issue from masticatory performance.

4.2. Differences in the effects of groove design

In this study, the presence of grooves in the occlusal surface resulted in greater masticatory efficiency. The grooves accelerated the comminution of food materials, particularly fiber-rich foods. In general, it seems reasonable to expect greater masticatory performance with a smaller inter-groove distance. However, this study revealed that only G3 had significantly smaller HI and SI values than G(−), indicating significantly greater masticatory efficiency. Therefore, it can be assumed that the presence of narrow flat surfaces between the grooves also plays an important role in compressing medium-sized food particles during mastication. Because compression between flat surfaces requires a higher pressure than grating between opposing edges of grooves, it is possible that G1 could improve masticatory performance in patients with a lower maximum occlusal force. In this study, the occlusal force was set at 52.9 N (5.4 kgf) on the mandibular first molar. This occlusal force was chosen based on the mean occlusal force of complete denture wearers reported by Watanabe [11]. Future studies are needed to clarify the relationship between groove design and masticatory performance under lower occlusal forces.

Regarding groove depth, this study demonstrated significant differences between G2 and G2(0.5), indicating that deeper grooves result in greater masticatory efficiency. This finding is consistent with our clinical experience in edentulous patients: shallow grooves are not as effective at ameliorating pain on the alveolar ridge. Because grooves with too much depth can cause tipping of artificial tooth materials, a depth of 1 mm may be clinically acceptable. Figure 1b shows one of our clinical patients with artificial teeth with 1-mm groove depth; only slight tipping is evident on the top of the buccal cusp of the mandibular right second premolar after 1.5 years of use. Although we expect that a groove depth of 1 mm would decrease denture soreness on the mandibular ridge and improve dietary intake by decreasing mechanical loading on the mucosal surface, these effects must be clarified in future clinical studies.

4.3. Masticatory movement

In the present study, numbers of masticatory cycles ranging from 3 to 21 were used. Maximal masticatory cycles of 21 was adopted according to our preliminary experiment, in which 21 cycles was the minimal masticatory cycles where at least one occlusal surface design showed HI and SI of normal range in each test food.

Considering daily food intake, numbers of mastication is one of the most important factors which regulate comminution of foods. However, as well known, numbers of mastication is affected by many factors, e.g. food texture, amount of food to chew and so on. Koshino et al. [21] reported, using peanuts as test food, that the mean number of mastication was 21.9±11.3 for healthy young dentate and 33.1±5.1 for complete denture wearers, where the number of mastication was evaluated in relation to swallowing threshold. However, on the contrary, Anai et al. [22] reported, using video observation of daily meal, that institutionalized elderly group showed smaller number of masticatory cycles than healthy young adult group. These findings well represent the difficulty in determining any single experimental masticatory cycle condition. As the present study focused on the comparison of the masticatory efficacy of different occlusal surface design, especially in the early stage of comminution before the comminution reached the normal range.

Therefore, the experimental masticatory cycles in this study was set up to 21 cycles as described above.

In order to simulate the mastication with complete dentures as much as possible, the experimental dentures were placed on silicone simulated mucosa and the mandibular movement path was set to be a tear-drop shaped. However, as a limitation of this study, only one set of the conditions could be reproduced on the simulator in this study. Although setting one condition would be effective to fairly compare the difference between the designs, the possible effect of other condition, i.e. different mandibular movement path like a chopping movement pattern, could not be evaluated. This would be a limitation of this study.

4.4. Masticatory efficiency and nutrition intake

Satisfactory diet would be an important issue when we discuss the health of elderly. Ikebe (2015) [23] suggested that chewing disorder can lead to avoidance of foods considered difficult to chew and a preference for soft, easily chewable foods. However, as suggested by Allen and McMillan (2002) [24], even after the quality of denture prostheses was improved, apparently successful prosthetic rehabilitation does not necessarily result in a satisfactory diet in the absence of tailored dietary advice. As suggested by Boven et al. (2015) [25] in their review article, a diet is a habit and it seems that by just improving the dental situation, the dietary habit does not change. Therefore, needless to say, the occlusal surface design reported in this study would not directly be linked to the improvement of nutrition intake. However, the improvement of mastication difficulty in patients with complete dentures, which we often observe in our clinic using the grooved artificial teeth, and the results showing significantly high masticatory efficiency in this study would suggest that the grooved design would provide the prosthesis performance ready to improve their dietary intake.

4.5. Occlusal surface design

More complete chewing of a food bolus is required for patients with dysphagia than for elderly people without dysphagia [26]. For very old edentulous patients with highly resorbed alveolar ridges, the following four items are necessary characteristics of artificial posterior teeth. First, to minimize the force exerted on the alveolar ridge, an effective chopping function is required. Second, to create an appropriate bolus from soft and/or granulated foods for smooth deglutition, wide opposing occlusal tables are required. Third, an effective shredding function is necessary to finely shred fibrous foods with minimum masticatory force. Fourth, an occlusal design compatible with any previously established occlusal schemes is required so that the artificial teeth can be applied to a variety of residual ridge conditions. To meet these requirements, we designed novel occlusal surfaces for artificial posterior teeth in this study. The deep grooves were intended to lessen the mechanical load exerted on the alveolar ridge by increasing the penetrative force per unit area, even when the bucco-lingual width of the molar occlusal table was wide. The opposing grooves were designed to cross, similar to the cutting action of scissors, to improve their shredding and comminuting functions. Because the opposing grooves were at right angles to each other, they did not interfere with each other or stub on the opposing occlusal structures. Therefore, the tooth designs did not require any specialized occlusal schemes and could be used according to previously established schemes such as full-balanced occlusion or lingualized occlusion. However, these requirements are largely conjectural and conceptual. A comprehensive evaluation of masticatory efficiency and nutrition intake using crossover study design is necessary in future studies.

This study revealed that a grooved occlusal surface design, with grooves 1 mm in depth and a groove interval of 2–3 mm, resulted in significantly higher masticatory efficiency than conventional occlusal surface design. The clinical efficacy of this occlusal surface must be clarified in future crossover studies to comprehensively evaluate masticatory efficiency in elderly edentulous patients.

5. Conclusions

A grooved occlusal surface design, with grooves 1 mm in depth and a groove interval of 2–3 mm, resulted in significantly greater masticatory efficiency than conventional occlusal surface design when evaluated with a masticatory simulator. It is noteworthy that the improvement in masticatory efficacy was prominent for raw leafy vegetables, which elderly people tend to have difficulty eating.

Acknowledgment

This work was supported by the Translational Research Network Program, A10.

Conflicts of interest

The authors declare no conflict of interest.

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FIGURE LEGENDS

Fig. 1. Grooves ground on artificial teeth. (a) Schematic diagrams of the grooves on the occlusal surfaces of artificial teeth. (b) Example of a clinical case with grooves on artificial teeth, after 1.5 years of use. Note that the grooves are angled at 45° to the dental arch and the grooves on the artificial teeth are orthogonally oriented to the opposing grooves when occluded.

Fig. 2. Complete denture masticatory simulator. (a) Schematic diagram of the masticatory simulator. The masticatory simulator was installed on a power bench to generate jaw opening force (open arrow) applied to PR. Prescribed amount of occlusal force was generated by the weight (W). (b) Measured incisal path during mastication. Note that the incisal path shows a typical teardrop form for the jaw-closing phase. W: weight; SD: ring for lateral spring and damper; PR: pull-up ring; GR: guiding rod for mandibular movement; GP: guiding plate for mandibular movement; SL: silicone layer as artificial mucosa; ICP: intercuspal position.

Fig. 3. Example of digitized pictures of masticated lettuce particles. Note that the food particles produced with the G2 groove after 15 masticatory cycles are efficiently shredded

compared with other conditions.

Fig. 4. Effects of mastication with grooved artificial teeth on HI and SI. The dotted lines show the thresholds for the range of normal mastication for HI (0.10) and SI (1.62) reported by Sugimoto et al. [14, 17].

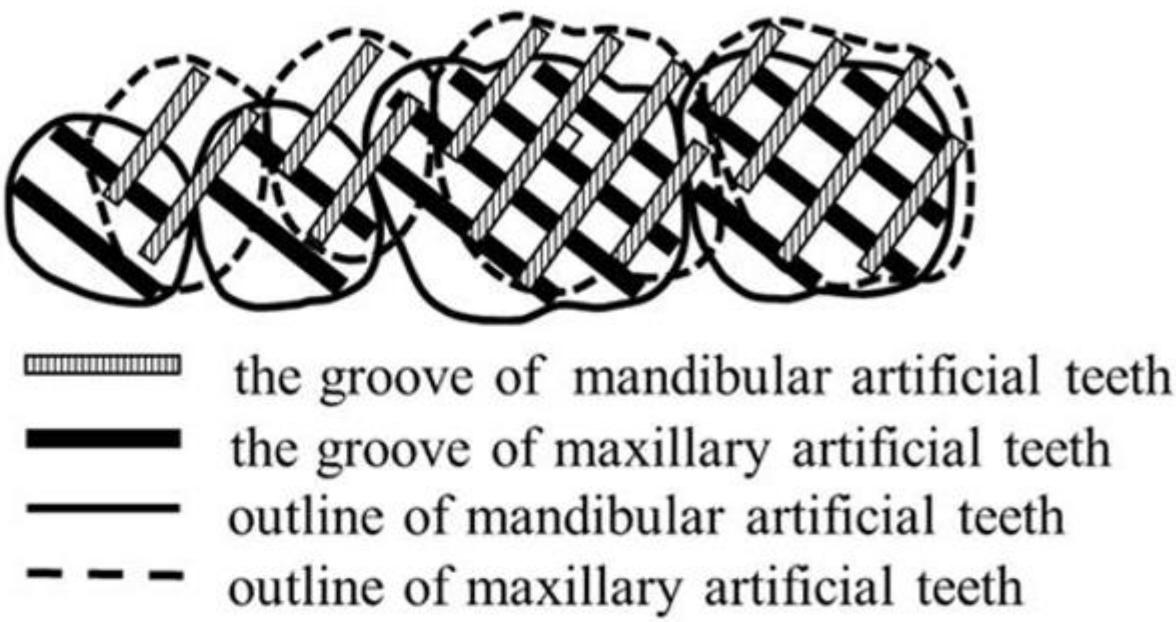
the groove of mandibular artificial teeth
the groove of maxillary artificial teeth
outline of mandibular artificial teeth
outline of maxillary artificial teeth

Fig 1 (a)

Fig 1 (b)

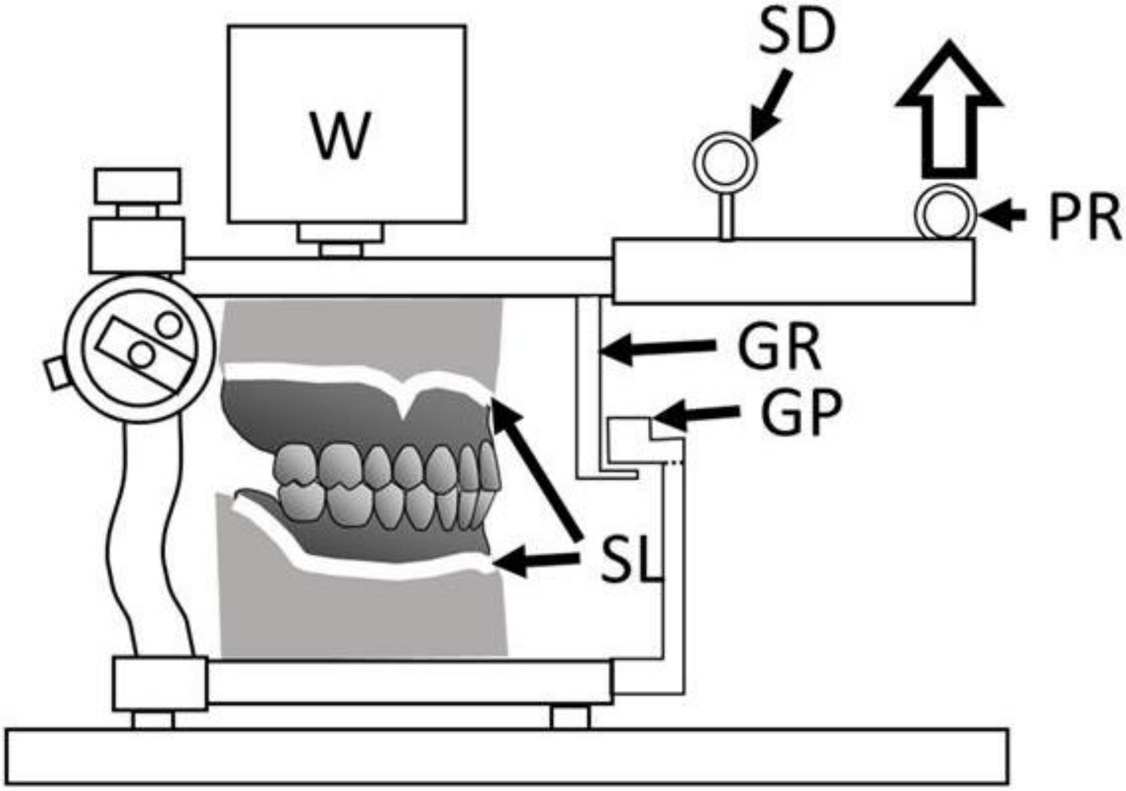

Fig 2 (a)

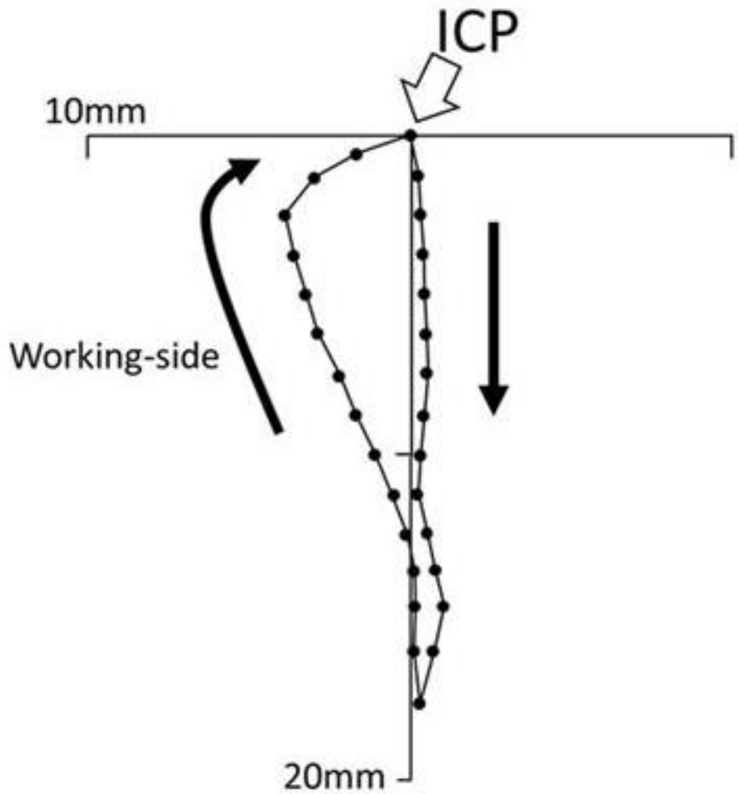

Fig 2 (b)

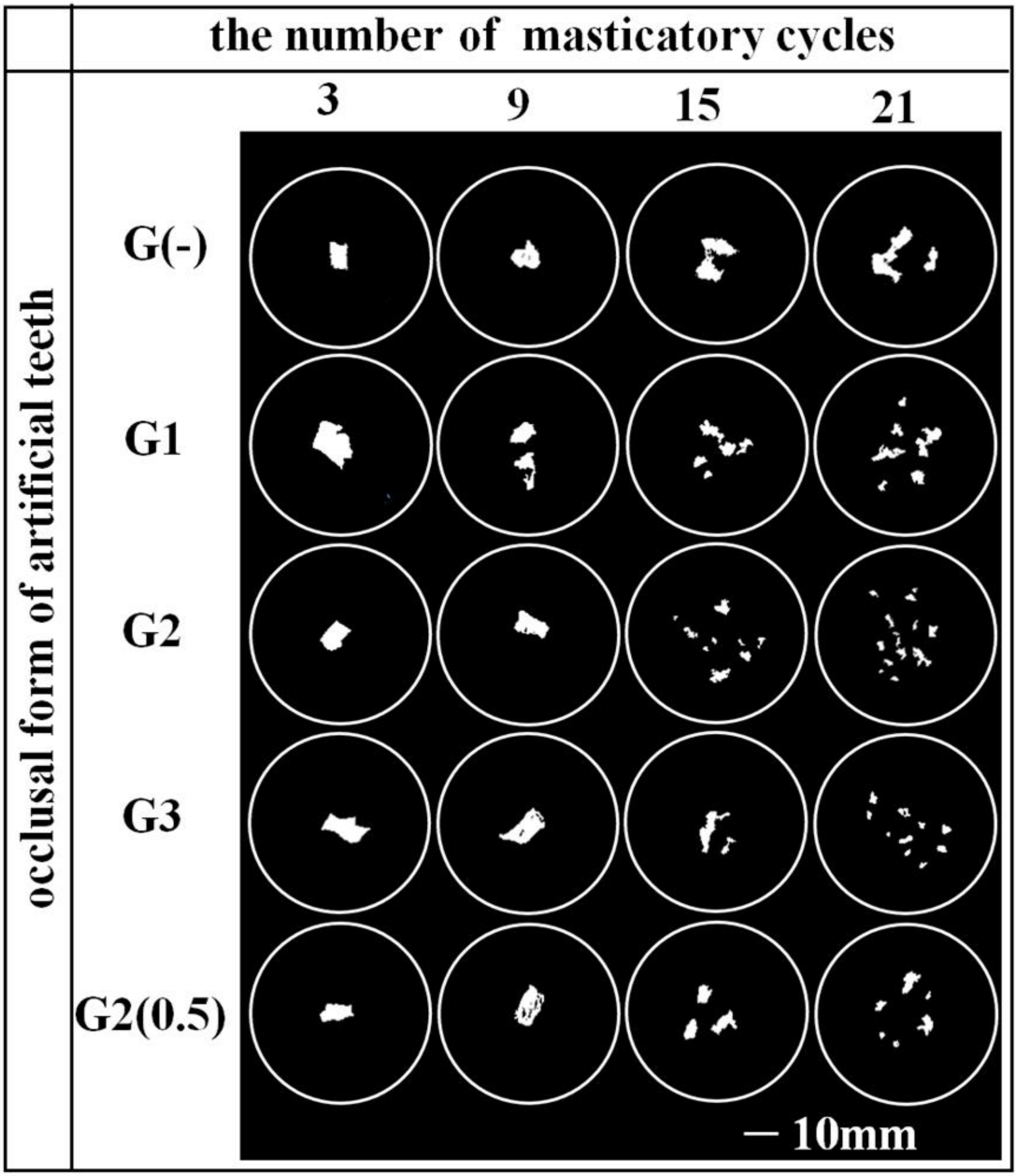
the number of masticatory cycles
occlusal form of artificial teeth
3
9
15
21
G(-)
G1
G2
G3
G2(0.5)
10mm

Fig 3

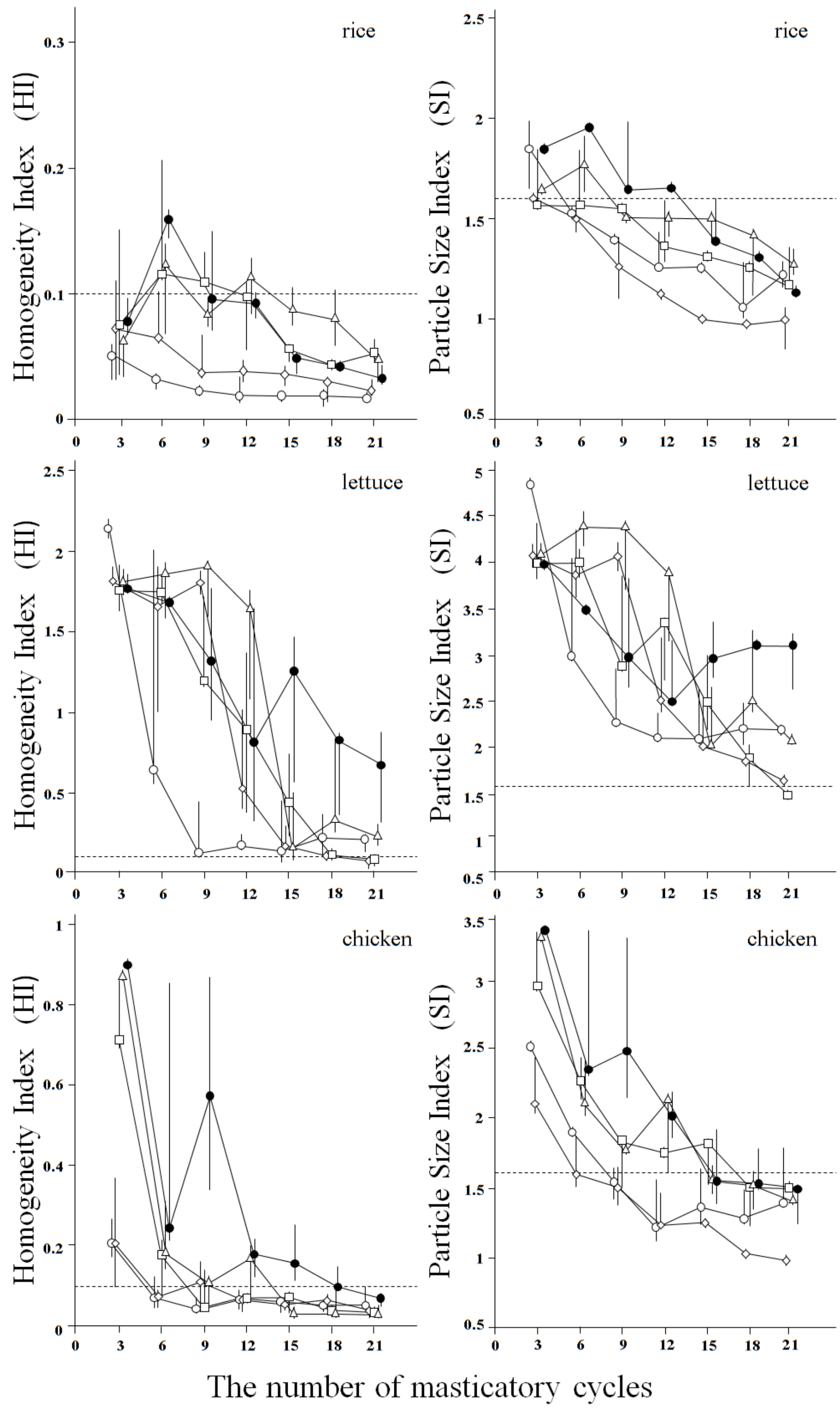
rice
lettuce
chicken
Homogeneity Index (HI)
Particle Size Index (SI)
0
0.1
0.2
0.3
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0.4
0.6
0.8
3
6
9
12
15
18
21
The number of masticatory cycles

Fig 4

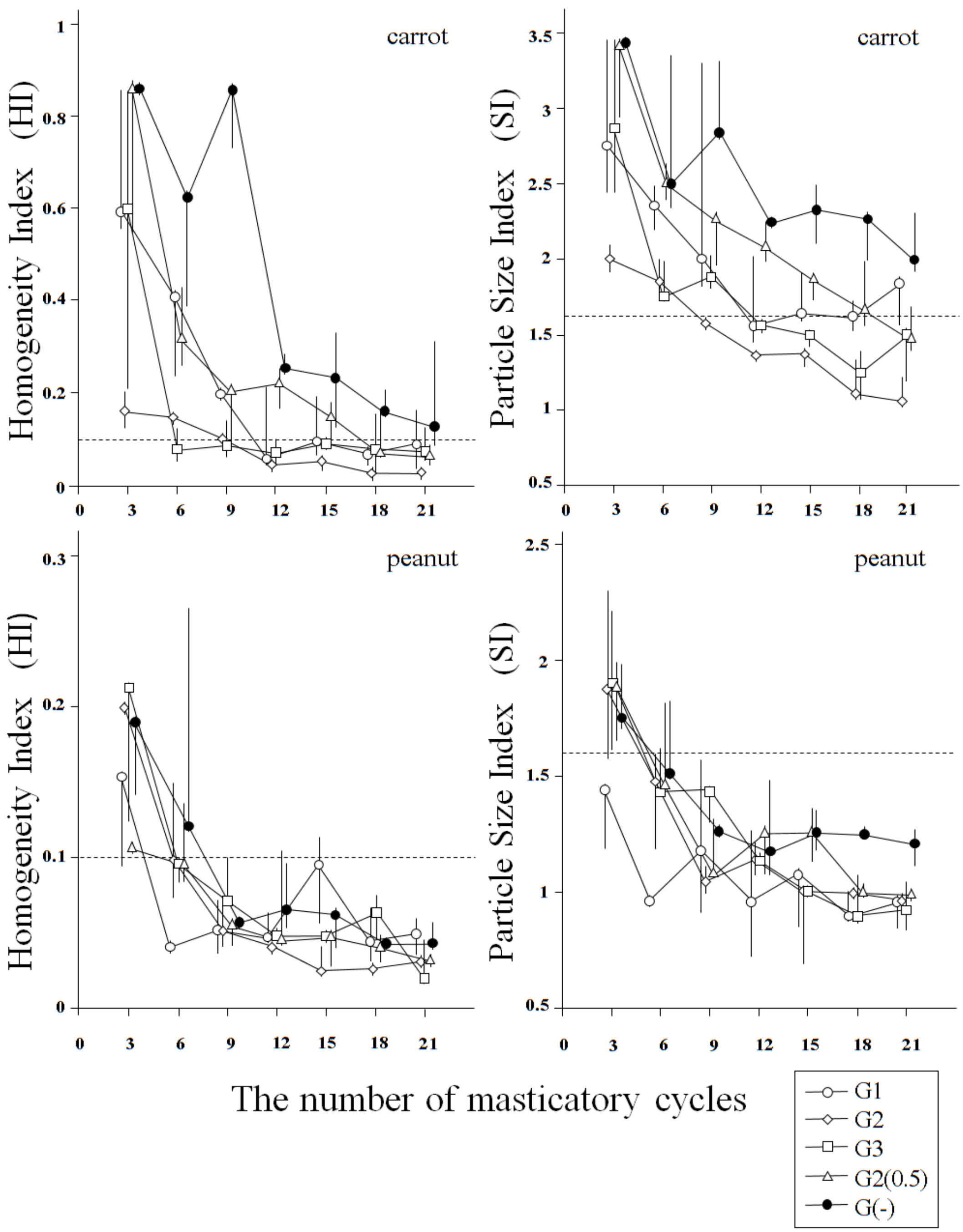
carrot
Homogeneity Index (HI)
Particle Size Index (SI)
peanut
The number of masticatory cycles
G1
G2
G3
G2(0.5)
G(-)

Fig 4

Table 1 – Statistical differences between different groove designs for the food materials tested.

Food material	Match-up	MC	HI	SI
Rice	G(–) versus G1	6	*	
	G(–) versus G2	9		*
		12		*
	G1 versus G3	21	*	
	G1 versus G2(0.5)	15	*	
	G2 versus G2(0.5)	15	*	
Lettuce	G(–) versus G3	21	*	*
Chicken breasts	G(–) versus G1	9	*	
	G(–) versus G2	6	*	*
	G(–) versus G2(0.5)	15	*	
Carrots	G(–) versus G2	12	*	*
		18	*	*
		21		*
	G(–) versus G3	6	*	
Peanuts	G(–) versus G1	18		*

MC: masticatory cycles; HI: homogeneity index; SI: particle size index.

* $p < 0.05$.

Table 1