Developing a New Appliance to Dissipate Mechanical Load on Teeth and Improve Limitation of Vertical Mouth Opening

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ABSTRACT

Objectives: The principle of leverage to superpose the convex surfaces of two shells was applied to develop a device for treating limitation of mouth opening and called it the "shell-shaped mouth opener" and analyzed pressure on the teeth with the TheraBite® appliance and the shell-shaped mouth opening appliance.
Material and Methods: To compare the TheraBite® appliance and the shell-shaped mouth opening appliance, pressure on the teeth in the dentition model with both devices was analyzed using the Inastomer® flexible conductive sensor.
Results: The load was better dispersed to each tooth in the shell-shaped mouth opening appliance in the all quadrants compared to the TheraBite® appliance.
Conclusions: The present study revealed that the shell-shaped mouth opening appliance which was originally invented in our lab, dissipated the mechanical load on teeth more evenly than the TheraBite® appliance.

Keywords: mouth rehabilitation; dental stress analysis.

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INTRODUCTION

The limitation of mouth opening is a condition marked by orofacial pain and a limited ability to open the mouth and can result due to tumours, trauma, inflammation, intra- or extracapsular disorders of the temporomandibular joint (TMJ) [1-3]. Patients with limitation of mouth opening experience multiple problems related to exhibit restricted chewing, swallowing, and speaking [2]. They also require extra care for maintaining oral hygiene [2]. A variety of mouth opening appliances including rubber plugs, wooden tongue blades, and the TheraBite® Jaw Motion Rehabilitation System™ (Atos Medical Inc., West Allis, WI, USA) have been used to treat the condition of mouth opening limitation [4]. The TheraBite® appliance has shown greater efficacy than any other treatments [5,6]. It is a useful appliance for patients with sustained trismus particularly for those having undergone treatments for head and neck cancers [5,7]. It consists of two mouthpieces and the attached plastic handles. The mouthpieces are inserted between teeth of the upper and lower jaws. The patient's mouth can be opened by pressing together the plastic handles that force the mouthpieces to separate [2]. Some researchers revealed that muscular problems cause the limitation of mouth opening [8,9]. Other group implied that use of the TheraBite® appliance results in pain because of the consequent rebounding spasms of the masticatory muscles [4] and this is because the TheraBite® appliance is a high-torque appliance that provides a short-duration passive stretch [4]. In some cases, the fracture of a titanium reconstruction plates during the TheraBite® appliance exercises is an adverse effect that can be explained by non-union of the fibula to the mandible, by the recurrence of carcinoma, or by excessive stretching forces [10]. When prescribing exercises with the TheraBite® appliance in cases of bony reconstructions of the mandible, exercise forces should be limited until consolidation of the reconstruction is completed [10]. However, it was not previously reported how the high-torque using by the TheraBite® appliance affected the pressure balance to teeth. In general, all mouth opening appliances only assist in simple jaw opening movements. To overcome these drawbacks, a new appliance was developed for treating limitation in mouth opening. Moreover, the pressure balance to the teeth using by the TheraBite® appliance or a new appliance was investigated by using the Inastomer® (Inaba Rubber Co. Ltd., Osaka, Japan) flexible conductive sensor.

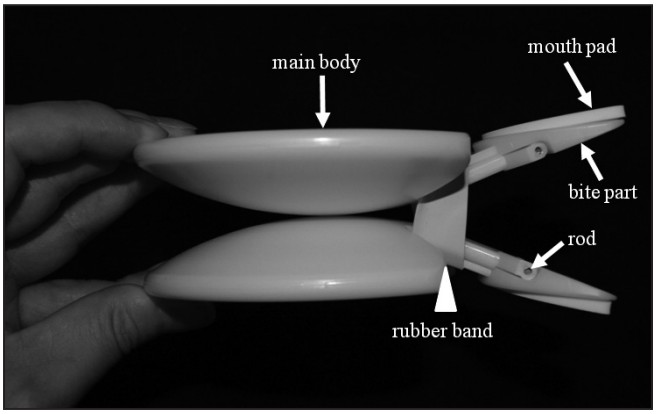


Figure 1. The shell-shaped mouth opening appliance consists of two main bodies, rods, bite-parts, mouth pads, and a rubber band. The main bodies superpose at their convex surfaces. The bite-part is attached to the base of the main body. A stainless steel rod (diameter: 2 mm) penetrates the bite-part and base of the main body. The base of the bite-part overlaps the base of the main body and the two main bodies are held together with a rubber band.

MATERIAL AND METHODS

Developing a new device

The principle of leverage to superpose the convex surfaces of two shells was applied to develop a device for treating limitation of opening and called it the "shell-shaped mouth opener" and further improved it to adapt to complex mandibular movements. Figure 1 shows this new device that consists of two main bodies and bases, two rods, two bite-parts and bases, mouth pads, and a rubber band. The main bodies superpose at their convex surfaces and the bite-part is attached to the body base. A stainless steel rod (2 mm diameter) penetrates through the bite-part and body base, contributing to its flexibility. The base of the bite-part overlaps the body base and the two main bodies are held together with a rubber band. The bite-parts are fitted with mouth pads made of polyethylene foam sheets, which act as a buffer and counterbalance the mechanical stress and torque against teeth. A new device is made of acrylonitrile-butadiene-styrene (ABS) resins.

The mechanism of the "shell-shaped mouth opener" involves a fulcrum that superposes the convex surfaces of the main bodies, a power point that is formed when the patient grasps the edges of the bodies, and a point of action that involves the bite-parts. The leverage at the main bodies and bite-parts and the hinge movement at the main bodies act together adjusting the complex three-dimensional movements. The combination of leverage and hinge movements of the "shell-shaped mouth opener" enables it to adapt to the left-right asymmetric mandibular movements (Figure 2A - C). Moreover, when the patient grasps and eases the edge of the main bodies, the rubber band at the base of the bite-part expands and contracts gently to prevent added torque to the teeth and masticatory muscles.

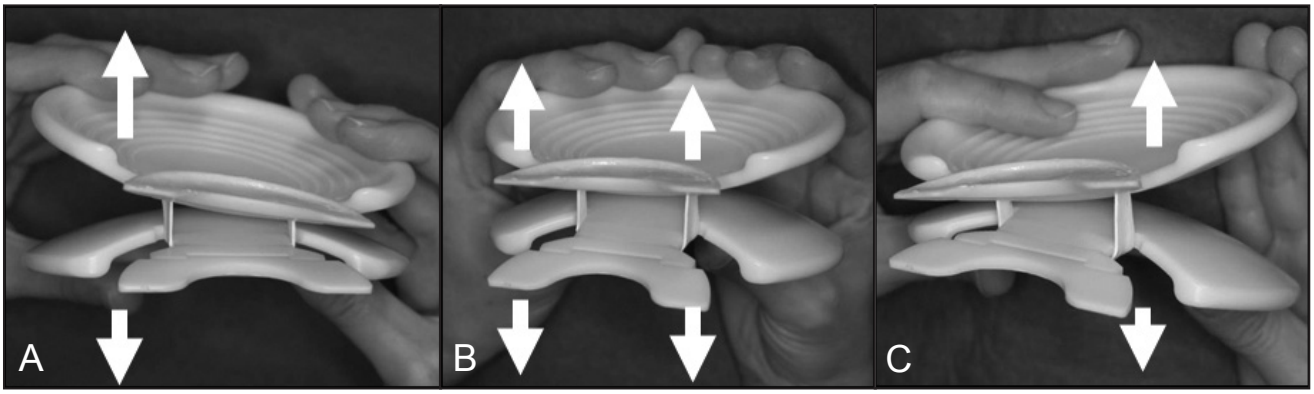


Figure 2. (A) When the patient grasps the right edges of the main bodies, the shell-shaped mouth opening appliance opens on the left side; (B) when the patient grasps both edges of the main bodies, the appliance opens on both sides; (C) when the patient grasps the left edges of the main bodies, the appliance opens on the right side. Arrows indicate the direction of action.

Analysis of pressure on teeth

To compare the efficacy of the TheraBite® appliance and the shell-shaped mouth opening appliance, pressure on the teeth with either of the appliances in situ was analyzed using the Inastomer® flexible conductive sensor (Figure 3A). The Inastomer® sensors were attached at roots of each tooth in the dentition model and connected microcomputer. Electric resistance was measured by microcomputer. The Inastomer® sensor is made with insulating rubber and electroconductive materials. When pressure is applied, the electroconductive materials make contact and conductive routes are formed and electric resistance is decreased. This is because the relationship between electric resistance and mechanical loading is inversely proportional. F-R property data of the Inastomer® sensor (Figure 3B) which was provided by Inaba Rubber Co. Ltd. (Osaka, Japan) was adjusted using the Lagrange interpolating polynomial under the following conditions: temperature at 24.7 °C; loading at 3 kgf; and loading speed at 200 mm/min. Corrected F-R property data (Figure 3C) was used for analysis. Load value on each tooth was measured three times and the average was adopted as data. Statistical analysis was performed by Welch's *t* test and the number at significance level of $P < 0.05$ is red colour (Figures 4 - 7).

The two-digit system for the dental formula was used:

$$y = y_i N_0(x) + y_{i+1} N_1(x) + \cdots + y_{i+m} N_m(x)$$

The Lagrange interpolating polynomial:

$$N_k(x) = \prod_{\substack{j=0 \\ j \neq k}}^{m} \frac{x - x_j}{x_k - x_j}$$

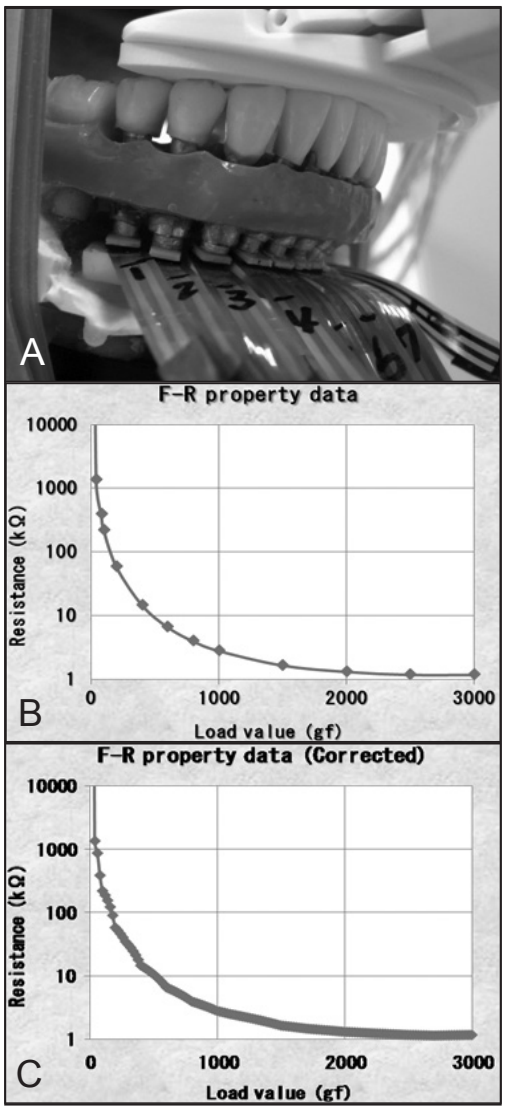
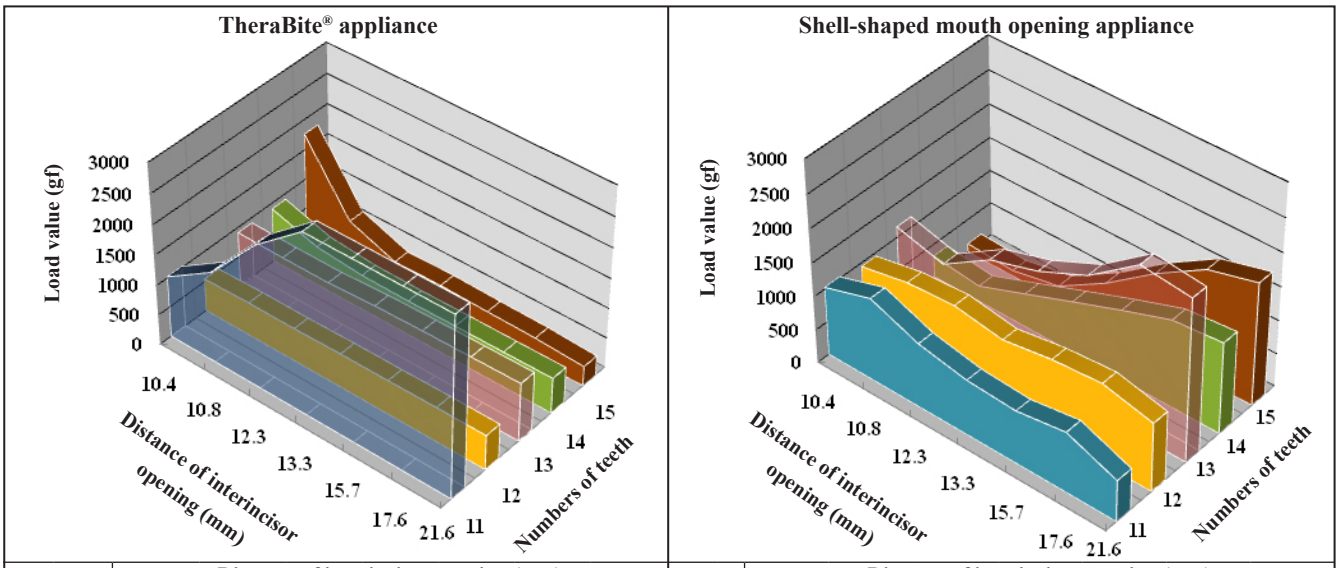


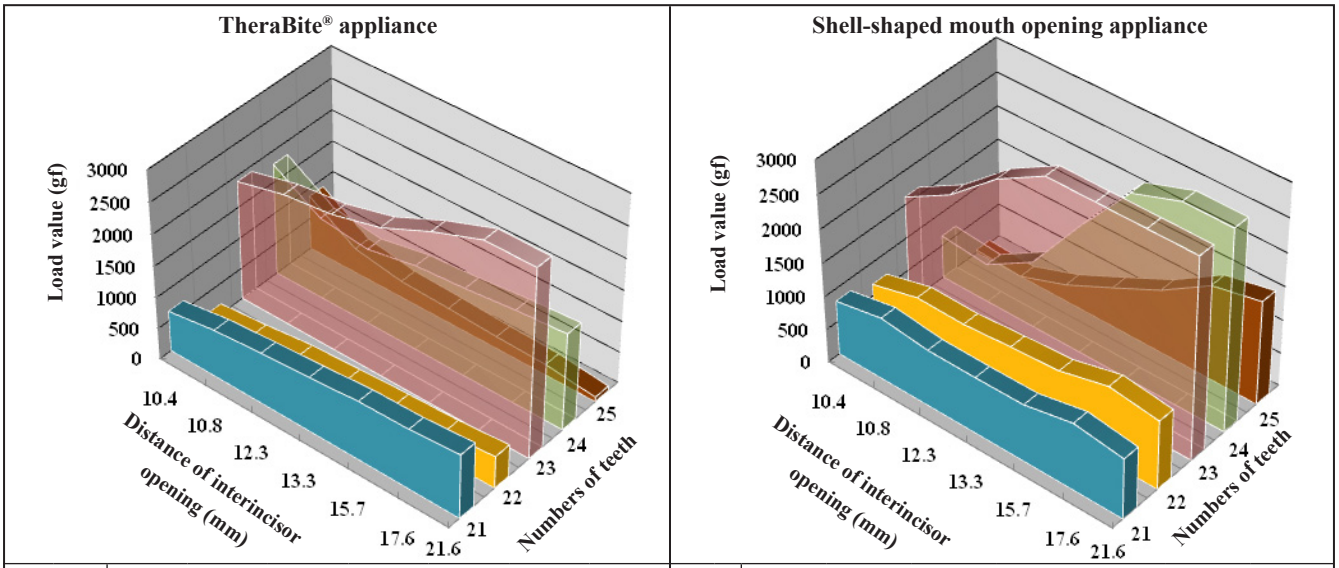
Figure 3. The mouth pads of both the TheraBite® and the shell-shaped mouth opening appliance are fitted over the patients' teeth. Each Inastomer® is attached to the surface of the roots of each tooth. When the load is applied to the TheraBite® or the shell-shaped mouth opening appliances, Inastomer® analyzes the electric resistance on the roots of each tooth (A). F-R property data of the Inastomer® sensor is shown (B). F-R property data was corrected by the Lagrange interpolating polynomial. Corrected F-R property data is shown (C).



TheraBite®		Distance of interincisor opening (mm)						
		10.4	10.8	12.3	13.3	15.7	17.6	21.6
		Load value (gf)						
Numbers of teeth	11	1015.94	1511.52	2373.52	3000	3000	3000	3000
	12	544.62	562.77	558.66	572.99	573.28	580.46	577.56
	13	910.91	898.15	896.8	937.14	954.95	964.63	973.57
	14	900.58	659.09	587.41	575.95	583.6	585.26	590.63
	15	1762.21	679.28	390.34	403.75	382.36	368.66	324.89

Shell-shaped		Distance of interincisor opening (mm)						
		10.4	10.8	12.3	13.3	15.7	17.6	21.6
		Load value (gf)						
Numbers of teeth	11	1023.96	1248.8	973.38	836.93	797.24	906.54	620
	12	942.66	1084.91	1134.38	1023.05	1137.72	1196.84	1030.71
	13	1155.66	968.99	1417.97	1635.57	1959.13	2500.56	2420.89
	14	319.63	236.57	505.74	779.6	1047.36	1300.72	1365.53
	15	123.7	83.38	226.7	663.65	1197.56	1644.4	1836.53

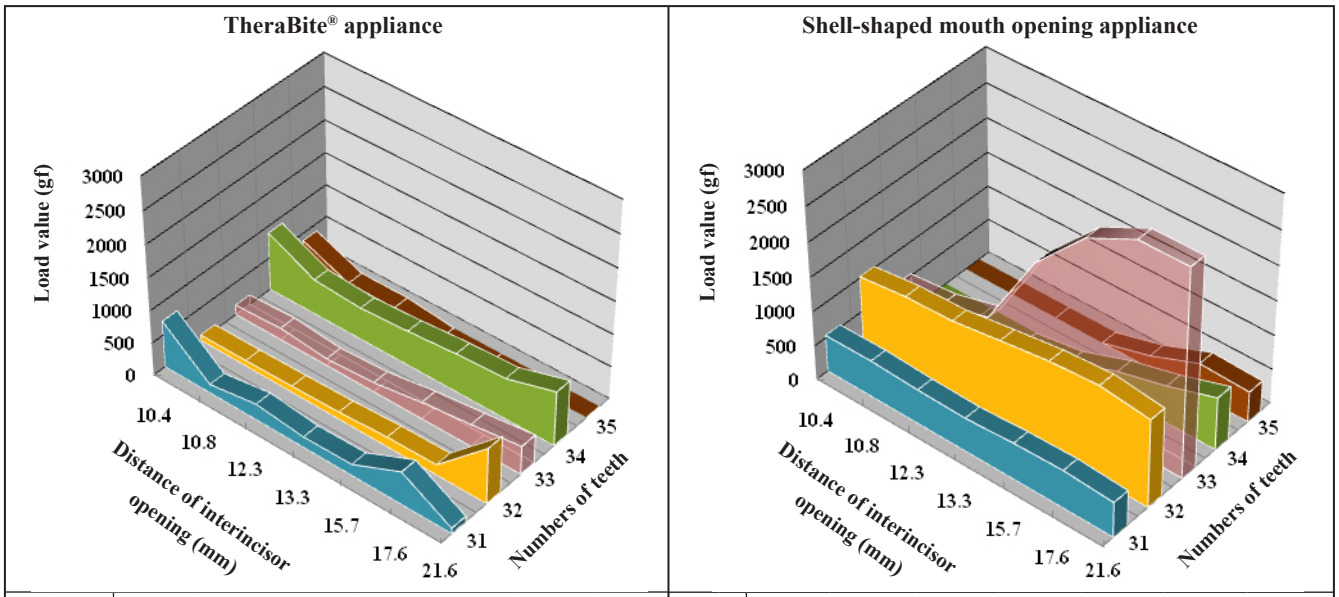
Figure 4. Results of pressure monitoring on teeth by mouth opening appliances (11 - 15). When the distance of the interincisor opening reached 13.3 mm, the central incisor was loaded at 3 kgf, which was greater than that for other teeth in the TheraBite® appliance. On the other hand, as the distance of interincisor opening was gradually increased, the canine and the first and second premolars were loaded gradually in the shell-shaped mouth opening appliance. In addition, the central and lateral incisors were loaded at all times in the shell-shaped mouth opening appliance.



TheraBite®		Distance of interincisor opening (mm)						
		10.4	10.8	12.3	13.3	15.7	17.6	21.6
		Load value (gf)						
Numbers of teeth	21	650.78	769.83	833.32	885.96	954.08	967.56	1030.32
	22	165.32	239.35	335.07	375.93	421.61	449.50	515.52
	23	1907.58	2093.83	2181.51	2376.25	2719.55	3000	3000
	24	1785.08	1311.89	1215.65	1361.87	1416.6	1497.06	1550.99
	25	870.13	397.87	263.59	234.33	191.94	167.02	73.1

Shell-shaped		Distance of interincisor opening (mm)						
		10.4	10.8	12.3	13.3	15.7	17.6	21.6
		Load value (gf)						
Numbers of teeth	21	813.9	948.75	863.14	859.7	867.29	1013.66	913.55
	22	673.79	857.76	846.9	905.88	953.5	1133.02	1037.4
	23	1612.48	2009.85	2598.74	3000	3000	3000	3000
	24	644.02	577.18	996.67	1915.99	2754.74	3000	3000
	25	40.46	0	253.17	595.09	946.26	1404.91	1556.57

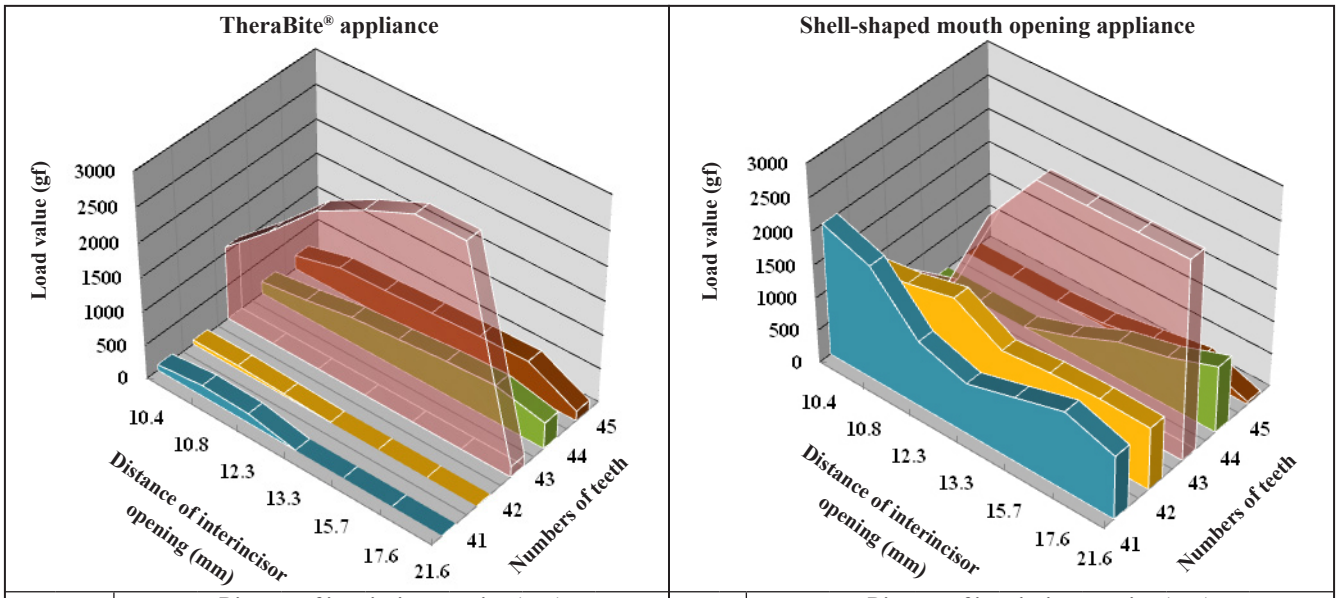
Figure 5. Results of pressure monitoring on teeth with mouth opening appliances (21 - 25). When the distance of the interincisor opening was increased, the canine was gradually loaded, but the load on the first and second premolars decreased using the TheraBite® appliance. Conversely, as the distance of the interincisor opening increased, the canine and the first and second premolars were loaded gradually in the shell-shaped mouth opening appliance. Additionally, the central and lateral incisors were loaded at all times in the shell-shaped mouth opening appliance.



TheraBite®	Distance of interincisor opening (mm)						
	10.4	10.8	12.3	13.3	15.7	17.6	21.6
	Load value (gf)						
Numbers of teeth 31	715.34	134.03	247.83	163.53	173.75	504.71	82.54
32	83.15	85.93	97.16	112.57	151.02	157.88	857.53
33	148.24	181.09	106.83	143.92	256.26	340.67	434.1
34	892.48	540.79	490.57	532.28	588.09	620.26	836.62
35	382.82	84.93	85.02	0	0	0	0

Shell-shaped	Distance of interincisor opening (mm)						
	10.4	10.8	12.3	13.3	15.7	17.6	21.6
	Load value (gf)						
Numbers of teeth 31	534.39	541.97	509.49	495.39	537.61	556.77	513.05
32	1017.1	1099.14	1124.39	1224.65	1319.97	1369.43	1282.84
33	530.18	599.4	785.57	1951.36	2658.07	3000	3000
34	0	0	0	105.06	359.57	541	767.75
15	0	0	0	0	192.74	470.27	443.02

Figure 6. Results of pressure monitoring on teeth with mouth opening appliances (31 - 35). All teeth were loaded weakly at all times using the TheraBite® appliance. As the distance of the interincisor opening was gradually increased, the canine was mainly loaded and the first and second premolars were loaded gradually in the shell-shaped mouth opening appliance. Moreover, the central and lateral incisors were loaded at all times in the shell-shaped mouth opening appliance.



TheraBite®	Distance of interincisor opening (mm)						
	10.4	10.8	12.3	13.3	15.7	17.6	21.6
	Load value (gf)						
Numbers of teeth 41	85.26	161.78	140.19	0	0	0	0
42	59.61	59.61	28.74	0	0	0	0
43	1077.85	1669.48	2324.51	2696.32	3000	3000	155.55
44	178.93	270.75	388.29	441.97	505.20	540.27	385.51
45	201.66	380.57	409.11	446.98	478.18	496.25	143.9

Shell-shaped	Distance of interincisor opening (mm)						
	10.4	10.8	12.3	13.3	15.7	17.6	21.6
	Load value (gf)						
Numbers of teeth 41	2008.92	1758.92	1014.63	783.04	993.21	1208.15	968.27
42	987.95	1093.76	1270.09	866.91	940.32	965.73	948.24
43	366.38	604.99	2106.68	3000	3000	3000	3000
44	0	0	0	253.92	573.97	750.21	1013.1
45	0	0	0	48.72	182.13	306.29	38.51

Figure 7. Results of pressure monitoring on teeth by mouth opening appliance (41 - 45). As the distance of the interincisor opening was gradually increased, the canine was strongly loaded in case of the TheraBite® appliance. When the interincisor opening distance reached 10.4 mm, the central and lateral incisors were loaded mainly in the shell-shaped mouth opening appliance. Furthermore, as the distance of the interincisor opening was gradually increased, the canine and first premolars were gradually loaded.

RESULTS

Pressure on teeth with the TheraBite® appliance and the shell-shaped mouth opening appliance

In the upper right quadrant, compared to the shell-shaped mouth opening appliance, the central incisor was loaded (Shell vs TheraBite® 11 at 21.6 mm P = 0.0056) and other teeth were not loaded diffusely in the TheraBite® appliance (Shell vs TheraBite® 12 at 21.6 mm P = 0.00000086, 13 at 21.6 mm P = 0.018, 14 at 21.6 mm P = 0.026, 15 at 21.6 mm P = 0.00045). However, the canine was partially loaded and other teeth were loaded diffusely in the shell-shaped mouth opening appliance. Moreover, the canine was gradually loaded as the interincisor opening was increased in the shell-shaped mouth opening appliance (Shell vs TheraBite® 13 at 12.3 mm P = 0.019, 13 at 13.3 mm P = 0.036, 13 at 15.7 mm P = 0.024, 13 at 17.6 mm P = 0.003, 13 at 21.6 mm P = 0.018). Furthermore, compared to the TheraBite® appliance, all teeth in the shell-shaped mouth opening appliance were loaded (Figure 4).

In the upper left quadrant, the canine was mainly loaded in TheraBite® appliance and the shell-shaped mouth opening appliance. The canine and the first premolar were partially loaded and the second premolar was gradually loaded as the interincisor opening was increased in the shell-shaped mouth opening appliance (Shell vs TheraBite® 25 at 15.7 mm P = 0.0067, 25 at 17.6 mm P = 0.0054, 25 at 21.6 mm P = 0.041). Additionally, compared to the TheraBite® appliance, the lateral incisors were loaded in the shell-shaped mouth opening appliance (Shell vs TheraBite® 22 at 10.4 mm P = 0.0045, 22 at 10.8 mm P = 0.001, 22 at 12.3 mm P = 0.021, 22 at 13.3 mm P = 0.018, 22 at 15.7 mm P = 0.015, 22 at 17.6 mm P = 0.0024, 22 at 21.6 mm P = 0.001) (Figure 5).

In the lower left quadrant, the first premolar was slightly loaded, but all teeth were weakly loaded in TheraBite® appliance. As the distance of the interincisor opening was gradually increased, the canine, the first premolar, and the second premolar were gradually loaded in the shell-shaped mouth opening appliance. Moreover, the lateral incisors were loaded in the shell-shaped mouth opening appliance (Shell vs TheraBite® 32 at 10.4 mm P = 0.0073, 32 at 10.8 mm P = 0.0054, 32 at 12.3 mm P = 0.0086, 32 at 13.3 mm P = 0.006, 32 at 15.7 mm P = 0.000096, 32 at 17.6 mm P = 0.000055, 32 at 21.6 mm P = 0.00015). Compared to the shell-shaped mouth opening appliance, all teeth in TheraBite® appliance were not loaded effectively in the lower left quadrant (Figure 6).

In lower right quadrant, as the distance of the interincisor opening was gradually increased, the canine was loaded in TheraBite® appliance and the shell-shaped mouth opening appliance. However, other teeth were not loaded effectively in the TheraBite® appliance. Compared to the TheraBite® appliance, the central (Shell vs TheraBite® 41 at 10.4 mm P = 0.00019, 41 at 10.8 mm P = 0.012, 41 at 12.3 mm P = 0.004, 41 at 13.3 mm P = 0.013, 41 at 15.7 mm P = 0.014, 41 at 17.6 mm P = 0.01, 41 at 21.6 mm P = 0.0000026) and lateral incisors (Shell vs TheraBite® 42 at 10.4 mm P = 0.00062, 42 at 10.8 mm P = 0.0089, 42 at 12.3 mm P = 0.000037, 42 at 13.3 mm P = 0.0044, 42 at 15.7 mm P = 0.0019, 42 at 17.6 mm P = 0.000097, 42 at 21.6 mm P = 0.00013) were loaded in the shell-shaped mouth opening appliance (Figure 7). These results indicated that the load was better dispersed to each tooth in the shell-shaped mouth opening appliance in the all quadrants compared to the TheraBite® appliance.

DISCUSSION

The limitation of mouth opening occurs frequently due to tumours, trauma, inflammation, TMJ disorders, and their treatment. Regardless of the relative commonness of this condition and its harmful effects on daily functioning and quality of life, there are only few studies concerning the treatment of limitation of mouth opening and no standard care exists [4]. Although physical therapy, hyperbaric oxygen [11], pentoxifylline [12], botulinum toxin injection [13], and surgical coronoidectomy [3] have been used for treating the condition. However, mouth opening appliances provide a conservative approach to therapy in addition to being easy to use and having better efficacy than physiotherapy and surgery [14,15]. Several mouth opening appliances have been developed for the treatment of limitation of mouth opening.

In the present study, the Inastomer® flexible conductive sensor was used to analyze the pressure on teeth. To our knowledge, there were no reports that the Inastomer® flexible conductive sensor was used to analyze the pressure on teeth. However, it is useful tool to measure the pressure on teeth. Analysis of pressure on teeth due to mouth opening appliances revealed that the shell-shaped mouth opening appliance dissipated the mechanical load on teeth more evenly than the TheraBite® appliance (Figures 4 - 7). Well-balanced load on teeth was relied on the constitution of the shell-shaped mouth opening appliance. The combination of leverage and hinge movements enabled the shell-shaped mouth opening appliance to adapt to complex mandibular movements, and the mouth pads helped to

evenly distribute the mechanical stress and torque. In this regard, the shell-shaped mouth opening appliance may be superior in reducing the overconcentration of particular tooth during the treatment of limitation of mouth opening, which is paramount for patient compliance and positive therapy outcomes [16] and contribute to avoid the fracture of a titanium reconstruction plates [10]. However, to confirm whether the shell-shaped mouth opening appliance is superior to the TheraBite® appliance, further research need to compare the TheraBite® appliance and the shell-shaped mouth opening appliance and to establish the best way to use the shell-shaped mouth opening appliance for the treatment of limitation of opening *in vivo* study.

CONCLUSIONS

The present study revealed that the shell-shaped mouth opening appliance dissipated the mechanical load on teeth more evenly than the TheraBite® appliance.

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